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CHERNOBYL, THREE MILE ISLAND AND BEYON
LESSONS FOR ONTARIO?

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CHERNOBYL, THREE MILE ISLAND AND BEYOND: LESSONS FOR ONTARIO?

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I

THE ISSUE

Nuclear power has been a fact of life in the developed world for two generations. It is a workhorse supplier of base electricity loads in Ontario, France, Belgium, Japan and many American states. Highly publicized accidents at Chernobyl, and to a lesser extent Three Mile Island, have raised public concern around the world about the safety of nuclear generating stations. Since the planning process which will guide the Province's power generation for the next 25 years is now under way, it is important that the public and elected officials understand how and why these and other nuclear accidents occurred and whether there are lessons to be learned in designing and operating CANDU facilities in Ontario.

This Current Issue Paper reviews major accidents which have occurred at commercial and military nuclear facilities, and provides basic background on nuclear power and reactor design features to assist the novice in understanding the very complex technical issues surrounding these events. Above all, the role of human factors in the prevention of potential accident situations is emphasized.

EXECUTIVE SUMMARY

Introduction

This Current Issue Paper reviews nuclear accidents at Three Mile Island, Chernobyl and elsewhere, and considers similarities and differences among these incidents to identify factors which are of relevance to Ontario's CANDU nuclear reactor program. Severe nuclear accidents are often defined as those which breach containment and expose the public to significant radiation doses, or when an accident ends the plant's useful operation.

Background

In nuclear power stations, a controlled nuclear reaction is used to generate heat and produce steam which drives a turbine to generate electricity. A number of designs have evolved which differ in the way the nuclear reaction is moderated (using ordinary water, heavy water or graphite), the substance used for cooling and heat transfer (gas, ordinary water, heavy water or liquid metal), and whether the reactor core directly heats the water to generate steam or uses a secondary loop to provide steam for the turbine. Each reactor technology has examples of successes and failures.

Nuclear safety philosophies depend first upon accident prevention, through strict regulation, quality control and inspections. Should an accident start, reactor designs include mitigating systems to shut down the reaction and prevent damage to the plant. The third line of defense is the station's accommodating system, whose role is to contain radioactivity released from the fuel.

Three Mile Island (TMI)

TMI is a pressurized, light-water reactor complex near Harrisburg, Pennsylvania. In March 1979, after less than one year's operation, a pump providing feed water to the reactor core of one unit clogged during full power operation. After the plant shut down automatically, a relief valve opened to diminish the built-up pressure and temperature, letting out steam and water. This open valve was not detected by operators, and in two hours almost a million gallons of coolant water escaped, exposing the core, causing some of the fuel to melt.

Radiation at TMI was largely confined to the reactor building itself due to containment facilities at the site. Only slight public exposure occurred, and no resultant health effects are expected. However, public alarm and associated stress were high and more than 2000 lawsuits claiming health and psychological damage are pending.

Major impacts include the permanent loss of the generating capacity of the reactor, a billion-dollar cleanup which exceeds the cost of building the reactor, and an inventory of radioactive debris and water with no functioning high-level nuclear waste repository in the USA. The greatest impact may be increased public fear and scepticism about nuclear power.

Chernobyl

The Chernobyl reactor was a boiling-water, graphite-moderated reactor of a type designated RBMK. It was situated in the Ukraine, with about 45,000 people living in the immediate area, and about 150,000 within 30 km.

During a procedures test, operators disabled several safety systems, and then operated the reactor at an unsafely low power level. A design characteristic called the "positive void" effect caused the reaction to speed up as coolant levels declined, resulting in a rapid power rise and a violent explosion which destroyed the reactor. This breached the plant's partial containment and released a large amount of radioactive fallout. Subsequently, the hot radioactive core and burning graphite moderator continued to release high levels of radiation for nine days.

A number of design features, including the positive void coefficient, a slow and clumsy control rod system, lack of independent shutdown systems, the use of graphite as a moderator and the lack of complete containment all contributed to the accident. However, deliberate operator errors, and an "it can't happen here" attitude were also essential components of the disaster.

Local impacts included at least 31 direct deaths, 237 cases of acute radiation exposure, and expected health effects for people living in the immediate area of the reactor. Risks for people beyond the USSR are speculative and are statistical in nature.

Several contaminated "hot-spots" remain in the Ukraine and Byelorussia. At least 200,000 people have been moved from their homes, and the accident is said to have contaminated almost five million hectares in the Ukraine along with 20% of neighbouring Byelorussia.

The economic costs of the accident at Chernobyl have not yet been fully calculated but are enormous. Direct and indirect costs may reach $15 billion, although the long-term costs to the USSR to deal with all consequences may be much higher. Agriculture was affected in Germany, the United Kingdom, Sweden and other countries where fallout accumulated to excessive levels.

Common Features of Three Mile Island and Chernobyl

Both accidents happened on the night shift, when operators did not pay attention to or did not believe their instruments. In each case reactor designs were sensitive to perturbations, and operators took steps to defeat safety systems. Training simulations had not anticipated accidents of the types that occurred, and operators had a poor understanding of nuclear physics and plant processes.

In both cases complacency was widespread at all levels. Neither country's nuclear industry believed that a major accident was possible.

Other Nuclear Accidents

In the 1950s, the NRX and NRU experimental reactors at Chalk River, Ontario experienced accidents which contributed to the design of the safety features found in the CANDU series of reactors. Other nuclear accidents have occurred in West Germany, the United Kingdom, the USSR, the United States and elsewhere. Military facilities were responsible for all the major accidental releases of radioactivity to the environment prior to Chernobyl. Isolation of military nuclear programs from the mainstream of science and technology has been cited as breeding complacency and ignorance of improved methodologies.

CANDU and Chernobyl

The CANDU reactor design is very different from the Soviet RBMK in that it uses a different moderator (heavy water versus graphite), coolant (heavy water versus light

water), fuel (natural uranium versus 2% enriched uranium) and has an indirect steam cycle, whereas, in the RBMK, steam from the reactor goes directly to the turbines. As well, the RBMK lacks full containment and has a slow shutdown system.

There are, however, three major similarities between the two reactor designs. The CANDU has a **positive void coefficient**, although smaller than that of the RBMK. This characteristic causes an increase in reactivity when coolant is lost, and was termed by the Ontario Nuclear Safety Review (Hare Commission) as one of CANDU's "less desirable characteristics." The CANDU designers initially responded to the challenge of a positive void factor with a faster and more substantial shutdown system, and, unlike the RBMK, most CANDU reactors have two fully effective and independent shutdown mechanisms. Experts note that every reactor design has the potential for large reactivity increases, but only the RBMK did not recognize this adequately.

A second common feature is that both the CANDU and RBMK designs can be **refuelled without shutting down** the reactors, meaning that the stations may produce power for a greater proportion of time than other designs. The RBMK's overhead fuelling gantry fell on the reactor during the Chernobyl accident, but the front and back fuelling of the CANDU would eliminate this possibility. Some experts noted that dispersing the fuel in rods as done in RBMK and CANDU has safety advantages compared with the bundling of fuel in other reactor designs.

A final common design feature is the use of **pressure tubes** in contrast with the large pressure vessels used in other reactor designs. While one report suggested that pressure tube failure may have been a major contributing factor to the Chernobyl accident, most analyses do not appear to include such a conclusion. Certainly premature tube failures have plagued Ontario's CANDU reactors, and the Hare Commission commented on this phenomenon at length. The present analyses appear to consider potential tube failures as a serious economic factor rather than a safety issue, but the Commission expressed concern regarding possible risks to workers, if not the public, and strongly recommended accelerated research efforts related to all aspects of premature pressure tube aging.

The use of pressure tubes does have many advantages, and some reviewers have noted that a catastrophic explosive rupture of the single pressure vessel in other reactor designs is an event for which containment systems offer little protection.

Human Factors

Both the Three Mile Island and Chernobyl accidents were characterized by major operator errors and a failure to anticipate the events which occurred when training crews. Isolation and complacency have been significant contributors to most severe nuclear accidents. This is particularly true of military facilities. An important requirement is that operational staff members have a good understanding of nuclear processes so that they fully appreciate the risks involved with non-standard operation of their plants. In retrospect, it becomes clear that for both Three Mile Island and Chernobyl, the regulatory agencies, managements, and operating staffs did not truly believe a major accident was possible.

Ontario Hydro has received favourable reviews from the Hare Commission and others regarding commitment to safety, quality of training, and other aspects required to develop a sound safety culture. Reports of understaffing and excessive stress, particularly at the senior operator level, and poor morale of other operations staff suggest that there is still room for improvement. Excellence in personnel performance in the design, construction, operation and maintenance functions may be more important than the type of technology used in assuring the safety of commercial nuclear power.

INTRODUCTION

Nuclear energy has been a part of life in the developed world for two generations. In each of the years 1984 and 1985, 33 new commercial nuclear power plants came into operation in the world, or one new plant every 11 days on average.[1] The world total of nuclear power plants in commercial operation in May 1990 was 428, with 26 countries now producing electricity from atomic energy.[2] France tops the list with 75% of its electricity coming from 54 operating units. Belgium is the runner-up with 61% and the Republic of Korea generates one-half of its power through nuclear means. The United States has 112 commercially-licensed nuclear plants, representing 20% of its electrical energy generation.

Few new nuclear power plants were ordered, particularly in the USA, since the 1970s. This hiatus appears to be largely due to the over-ordered situation in 1973, and there has been no reason for any US utility to order a power reactor since.[3] Over-building led to plants being completed when there was no need for the electricity or to plant construction being stretched out to avoid coming on-line when not needed. In either case, utility commissions looked sceptically at the costs. Lack of demand continues to be a major factor inhibiting the return on nuclear power in the United States. According to one respected analyst, this could change if large demand growth were perceived to be real, or indeed, if it were real.[4]

Nuclear power has several attractive features. Supplies of uranium fuel are plentiful in Ontario, Saskatchewan and elsewhere in Canada. The generating facilities emit no sulphur dioxide, nitrogen oxides or carbon dioxide. If the electric energy that was derived from nuclear power world-wide in 1988 had instead been produced by coal-fired plants, this would have given rise to additional emissions of carbon dioxide of about 1,600 million tons. The present pattern of demand for electricity has traditionally been met in most developed countries by either coal-fired or nuclear generating stations.

Misgivings about present and potential use of nuclear power largely relate to concerns about public and worker safety, radioactive waste disposal and the possible risk of proliferation of nuclear weapons. This paper considers only the first of these: certain aspects of safety. In particular, this is a review of several major nuclear accidents around the world, rather than an analysis of smaller, although important, in-plant

malfunctions or safety problems which may affect operating staff without directly putting the public-at-large at risk.

The Hare Commission, which recently reviewed the safety of Ontario's nuclear power reactors, defined a "severe" accident as one that breaches containment and releases sufficient radioactive material to expose the nearby public to significant doses.[5] Another recent review categorized reactors as "safety failures" when an accident ends their operation. This paper is generally guided by those definitions.

Risks of nuclear technology do exist. Complex technologies fail because of human and technical error, sometimes with serious results. The plant operators at Chernobyl were performing a safety check when they lost control of the reactor. Three Mile Island approached core meltdown because of a delay in the recognition of equipment malfunction.[6]

A recent analysis of the Chernobyl accident prepared for physicians made the following observation:[7]

> To live responsibly with modern technology, one must clearly describe and understand both the risks and the benefits. The equation should include preventative measures as well as a realistic plan for responding to nuclear accidents. This assessment process requires an arena rendered as open and democratic as possible, in the tradition of medical informed consent. Medical training focuses on the development of the capacities to evaluate risk, reduce error, and acknowledge either or both wherever they exist. If we examine the lessons of Chernobyl and our own experience of nuclear technology and disaster management in this light, we can learn from them.

This philosophy may provide a useful approach to considering the implications of the nuclear accidents which are described in this report. Neutral, objective debate regarding the risks and benefits of nuclear power is rare in the polarized information which appears in the media in Ontario and elsewhere. However, both aspects will have to be carefully considered if energy planning in the province is to proceed effectively.

BACKGROUND

General Principles of Nuclear Power

While the engineering problems of nuclear power are complicated, the underlying principles are simple.[8]

> Reactors produce heat by splitting the nuclei of such fissile elements as uranium and plutonium, packaged as fuel shaped into rods or pellets. Fission begins when a fissile isotope absorbs a neutron and decays into lighter elements, releasing energy in the form of recoiling fission fragments, gamma rays and a shower of energetic neutrons.
>
> The neutrons stimulate other atoms to fission, releasing yet more neutrons in a self-sustaining process called a chain reaction. Reactors tame the chain reaction by controlling the neutron population with neutron absorbing control rods and by reducing the neutrons' kinetic energy with moderating materials. The fuel, the control rods and moderator together constitute the reactor's core. Flowing coolant extracts the heat liberated in fission to make steam, which in turn spins the turbines that drive the electric generators. (Such cooling must continue even if the chain reaction is shut down, or else the decay of radioactive fission products will overheat the core, causing it to release its contents.)

Simply stated, a controlled nuclear reaction is used to generate heat and create steam which drives a turbine to produce electricity.

Types of Reactors

Nuclear reactors are usually defined in terms of the types of materials used to cool and moderate the reactions within.

The experience of nearly four decades has winnowed out designs for four basic types of reactors:[9]

- the heavy-water reactor (HWR);
- the light-water reactor (LWR);
- the gas-cooled reactor (GCR); and
- the liquid-metal-cooled reactor.

In heavy-water reactors, such as the CANDU family developed in Canada, the core is cooled and moderated by "heavy" water, so called because some of the hydrogen atoms have been replaced by deuterium, a rare, heavy isotope of hydrogen. The deuterium's cost is offset by the reactor's ability to use natural uranium, in which the rare, highly-fissile isotope uranium-235 has not been concentrated.[10] Canada is the major user of commercial HWRs in the world today.

Light-water reactors, in which ordinary water serves as both the coolant and the moderator, come in two versions; the boiling-water reactor (BWR) and the pressurized-water reactor (PWR). The BWR has a single thermal cycle wherein the core directly heats the water to generate steam. The PWR has two cycles; one employs a circulating loop of pressurized (hence, non-boiling) water to extract heat from the core, while the other uses that heat to generate steam. Both designs are in service throughout the industrialized world, in versions manufactured by companies in the United States, France, West Germany, Japan, Sweden and the USSR.[11]

Gas-cooled reactors have been built since 1956, at the beginning of the civilian nuclear power era.[12] Although the nuclear power industries of Great Britain and France were founded on versions of this technology, the high capital costs and low reliability association with the GCR have since led both countries to abandon it in favour of LWRs.

Liquid-metal-cooled reactors, designed in "breeder" configurations, produce more fuel than they consume by converting non-fissile uranium-238 (more than 98% of natural uranium) into fissile plutonium-239, a reactor fuel. Because breeders consume uranium so efficiently, they can give substantial electric energy independence to countries that lack indigenous uranium resources. However, the liquid-metal cōolant, generally sodium, is reactive with air and water, and so requires expensive measures to prevent chemical fires and explosions. Second, some fear that the plutonium produced would make the substance so widely available that an international traffic in the metal would result, impairing efforts to limit the proliferation of nuclear arms.[13]

A fifth category of nuclear power plant is also of interest, this being the Soviet RBMK, which uses solid graphite as a moderator and light water as a coolant to generate steam to run its turbines.[14] The USSR also designs and operates PWR stations. In the RBMK design, 2% enriched uranium oxide fuel is placed in about 1,660 vertical pressure tubes imbedded in graphite moderator blocks. The steam cycle is direct, in

that steam and water from the reactor are separated and steam goes directly to turbines.[15] The RBMK reactor will be discussed in more detail in a later section of this report.

Each reactor technology provides examples of success and failure. Most of the failures resulted from either human errors or subtle phenomena that were hard to anticipate.[16] Examples of safety and economic successes and failures among several reactor types are listed in Table 1. That American review did not consider heavy water reactors such as CANDU since they are not used in the United States.

Nuclear Safety Philosophy

The experience of industrialized countries has revealed vulnerability in current nuclear power plant designs that was not fully understood when the plants were designed. Among the most important concerns are human error, materials degradation, accidents resulting from chains of subtle failures, and the economic sensitivity of nuclear projects to disruption and poor workmanship.[17]

Reduction of these risks benefits the owner of the plant as well as the public since it is far more likely that an accident will destroy the value of a power plant than injure the people who live nearby. The accident at Three Mile Island, for instance, eliminated the equity in the plant but did not harm the surrounding population with respect to radioactive contamination.[18]

Essentially, there are two main safety issues with nuclear power plants:[19]

- are the reactors safe while operating normally? and
- what kind of accidents are possible and what would be their consequences?

In each case, the main threat is from exposure of workers and the public to dangerous radiation. Since almost all the radioactivity is in the fuel, and can only get out if the fuel overheats, the need is to control the power and keep cooling water on the fuel.[20] This involves three lines of defence:

- accident prevention;
- accident mitigation; and
- accident accommodation.

TABLE 1

Successes & Failures of Major Reactor Technologies

Light-water Reactors

Successes:	Plants in France, Switzerland, West Germany, Japan, Sweden, Finland, Korea and most plants in US.
Economic Failures:	Midland, Michigan; Zimmer, Ohio; Rancho Seco, California; Marble Hill, Ind.; Shoreham, L.I.
Safety Failure:	Three Mile Island 2, Pa.

Liquid-metal-cooled Reactors

Successes:	Phoenix, France; Dounreay, UK; Fast Flux Test Facility, Wash.; Experimental Breeder Reactor II, Idaho.
Economic Failure:	SNR 300, West Germany.
Safety Failures:	Fermi I, Mich.; Experimental Breeder Reactor I, Idaho.

Gas-cooled Reactors

Successes:	Peach Bottom, Pa.; AVR, West Germany.
Economic Failures:	Fort St. Vrain, Colo.; the gas reactor programs in France and UK; Thorium High-Temperature Reactor 300, West Germany.
Safety Failure:	Windscale, UK.

SUCCESSES AND FAILURES of the major reactor technologies are listed in this table. A plant is an economic failure when it costs so much or provides power so infrequently that it is not worth operating; it is a safety failure when an accident ends its operation. Three Mile Island plant 2, for example, is a safety failure because an accident in 1979 put it out of commission. The Shoreham, L.I., plant is an economic failure because state authorities will not allow its owners to recoup their investment.

Source: M.W. Golay and N.E. Todreas, "Advanced light-water reactors," Scientific American (April 1990): 87.

The following is a brief overview of the safety philosophy of Atomic Energy of Canada Limited and the Atomic Energy Control Board regarding the design, construction and operation of its CANDU reactors.

> Accident **prevention** is the most important thing to do, and it is done by strict quality control in manufacture and construction, by inspecting the plant while it's running, and by using operating experience to fix up small problems before they become large ones.
>
> If an accident starts, the next step is to arrest it before it damages the plant. In CANDU reactors, the normal control systems are powerful enough to do this for most accidents. They are backed up by separate systems dedicated only to safety - shutdown systems to turn off the power if it starts to go up higher than it should, and emergency core cooling, to replace cooling water if it should be lost from a pipe break. These are the CANDU **mitigating** systems.
>
> The CANDU goes one step further and allows for the possibility that fuel is damaged regardless, and so it has an **accommodating** system - containment - also a safety system, but whose role is to contain radioactivity released from the fuel. There is also a one-kilometer ring of land around the reactor - called the exclusion zone - which allows dilution of any radioactivity released in an accident before it can get to where people live.[21]

Clearly, accident prevention is the most effective way of ensuring safety. Should a reactor get out of hand and accident conditions arise, there is an immediate need for emergency measures. These are of three kinds:[22]

- restoration of the reactor to safe conditions, which is the responsibility of the operators in the control room and the other staff on duty at the time;
- emergency procedures within the station to protect workers and equipment and to prevent or minimize danger to the public; and
- emergency measures in the civil community around the station and (in severe cases) farther afield.

The recent Hare Commission, in its Ontario Nuclear Safety Review, examined the adequacy of these types of measures with respect to CANDU reactors operated by Ontario Hydro. That review should be consulted regarding details. Another aspect of

the nuclear safety philosophy that receives little public discussion is that of security, particularly from the action of terrorists. A team of commandos sent to test security at French nuclear power stations apparently penetrated one near Lyon with little difficulty. The commandos' sudden appearance in the central control room reportedly caused no concern, since the technicians assumed they must have been allowed entry.[23] In addition to carrying out the successful "penetration" test, security reviewers also found people who are on terrorist and criminal files employed by subcontractors and, in one case, former Red Brigade members were reported to have worked as cleaners at one nuclear site.

While Electricité de France officials dismiss many of these allegations as being "pure make-believe,"[24] it is clear that in today's world, the preparation and effective maintenance of sound security plans is essential to ensure the safety of any nuclear facility and the surrounding population.

THREE MILE ISLAND

The Plant

The Unit 2 reactor (TMI-2) was a pressurized-water facility (PWR)[25] situated on an island in the Susquhanna River, 12 miles southeast of Harrisburg, Pennsylvania. It and its undamaged twin were manufactured by Babcock and Wilcox at a cost of US $700 million.[26]

At 4:00 a.m. on March 28, 1979, TMI-2 was operating normally at nearly 100% rated power.[27] At this power level, about 2,700 megawatts of thermal energy were being generated by the reactor, which heats the primary coolant to 600°F at high pressure. This coolant was pumped through steam generators where it gave up its energy to create steam in the secondary loop, which drove a conventional steam turbine to generate about 1,000 megawatts of electrical energy. TMI-2 first went critical exactly one year to the day before the accident. It had been declared operational at the end of December 1978.

The Accident

Detailed chronologies of the accident at TMI-2 have been prepared by Jaffe (1981)[28] and by the US Nuclear Regulatory Commission's Special Inquiry Group.[29] The following is a brief synopsis of the major events:[30]

> The accident at TMI Unit 2 began after only 11 months of operation when a pump providing feedwater to the reactor core clogged during full power operation. After the plant shut down automatically, a relief valve opened to diminish the built-up pressure and temperature in the reactor, letting out steam and water.
>
> Undetected by the operators, this valve remained open for 2 hours, allowing the escape of nearly a million gallons of the coolant water covering the reactor fuel. As approximately half of the reactor core became uncovered, the radioactive water overflowed designed catchments, collecting in the basements of the reactor and auxiliary buildings. Without the coolant water, temperatures in the pressurized-water reactor rose quickly, causing some of the uranium fuel to melt.

Local Impacts

Radiation at TMI-2 was largely confined to the reactor building itself due to the containment facilities at the site. However, some public exposure did occur.

The accidental radiation received by people residing in the vicinity of TMI-2 came almost entirely from xenon-133 (half-life, 5.3 days), xenon-135 (half-life, 9.2 hours), and traces of radioactive iodine (principally iodine-131 (half-life, 9.0 days)), which escaped intermittently from the plant as gases.[31] Since these radioactive gases followed prevailing winds, they increased the level of ionizing radiation along their path; however, the increase was short-lived because xenon, which is relatively inert chemically and biologically, dispersed rapidly. Also, radioactive iodine was present only in barely detectable amounts to begin with. No release of long-lived fission products, such as strontium-90, caesium-137 and plutonium-239 was detected.[32]

Based on all of the available measurements, investigators concluded that the maximum cumulative whole-body radiation dose to anyone off-site was less than 100 millirems (mrem), that the average cumulative dose to those within 10 miles of the plant was about 8 mrem, and that the average cumulative dose to those within 50 miles of the plant was about 1.5 mrem. Because these estimates made no allowance for shielding by shelter or other attenuation factors, they were generally considered to represent overestimates.[33] Health workers came to the following conclusions:

> The only health impact of the Three Mile Island accident that can be identified with certainty is mental stress to those living in the vicinity of the plant, particularly pregnant women and families with teenagers and preschool children. Although increased risks of cancer, birth defects, and genetic abnormalities are potential long-term consequences of low-level irradiation, few if any such effects of the accident are likely, because the collective dose of radiation received by the population within a 50-mile radius of the plant was so small. Estimates of the number of people in the population who may ultimately experience any such effects range from 0.4 to 10, in comparison with hundreds of thousands in the same population who can be expected to develop cancer, birth defects, or genetic abnormalities through natural causes.[34]

An epidemiologist at Columbia University's School of Public Health has subsequently studied the incidence of cancer around Three Mile Island, using data from 69 small tracts that were within 16 km of the plant, and comparing them with national rates and with cancer rates in a data base for the Southeast Pennsylvania Region as a whole.[35] The 1990 study found no evidence that radiation released during the 1979 accident caused an increased risk of cancer in the area nearby.

More than 2,000 lawsuits claiming health and psychological damage from the TMI-2 accident are still pending[36] despite measurements after the event that showed that the highest possible whole-body dose to any one individual was less than 100 mrem, or only slightly greater than the average most people are exposed to from medical and dental radiation in a year.

Low levels of radioiodines and trace radioxenons collected in environmental samples (surface waters, effluent, vegetation, aquatic biota) taken from the area around TMI-2 indicated that releases of radioactive material from the accident were not environmentally significant. All of the off-site analytical results were significantly below regulatory limits.[37]

Other Impacts

The fact that significant amounts of radioactivity were not released from TMI-2 fortunately meant that there were no widespread health or ecological impacts. However, there have been many long-term implications of this accident. A recent review pointed out several of these:[38]

- A decade later, cleaning up the site continues at a cost of $1,000 million - nearly $300 million more than the cost of building the reactor in the first place.

- The "de-fueling" process should be complete by the end of 1990, when Unit 2 will be shut and monitored for about 30 years, until the end of the planned lifespan of the operating Unit 1 nearby. Both units would than be decommissioned and dismantled together.

- Because residual caesium has permeated the basement walls, unacceptable and potentially dangerous levels of radiation will remain until decommissioning.

- The generating capacity of Unit 2 is permanently lost.

- One hundred and fifty tons of highly radioactive debris have been removed from the reactor but, since there is not yet a functioning repository for high-level commercial nuclear waste in the US, it continues to be "temporarily" stored in Idaho.

- A plan to evaporate the remaining two million gallons of radioactive water at the TMI-2 site still awaited approval from the Nuclear Regulatory Commission in 1989.

- Most agree that the incident's greatest legacy is a sustained level of lingering public fear and opposition to nuclear power in the United States.

- Although performance has improved and dependence on nuclear power as a fraction of energy supply in the US has since grown, no new nuclear plants have been ordered since the accident, and all of the 47 units ordered in the US since 1974 have been cancelled.[39] (As noted earlier, over-supply of power plants for the existing demand for electricity was also a major factor in the lack of orders for new plants.)

In summary, while Three Mile Island may not have been a "severe" accident as defined by the Hare Commission, in that it did not breach containment and release sufficient radioactive material to expose the nearby public to significant doses,[40] the generating potential of TMI-2 was permanently lost and the psychological impact on the American population has resulted in lasting scepticism about nuclear energy. While the increasing US demand for electricity and growing concerns over gaseous emissions from fossil fuel-fired generating stations will likely result in resurging interest in advanced LWRs or newer designs for "inherently safe" reactors in the future,[41] the effect of the Three Mile Island accident on the industry and the US public can only be described as serious.

CHERNOBYL

The Plant

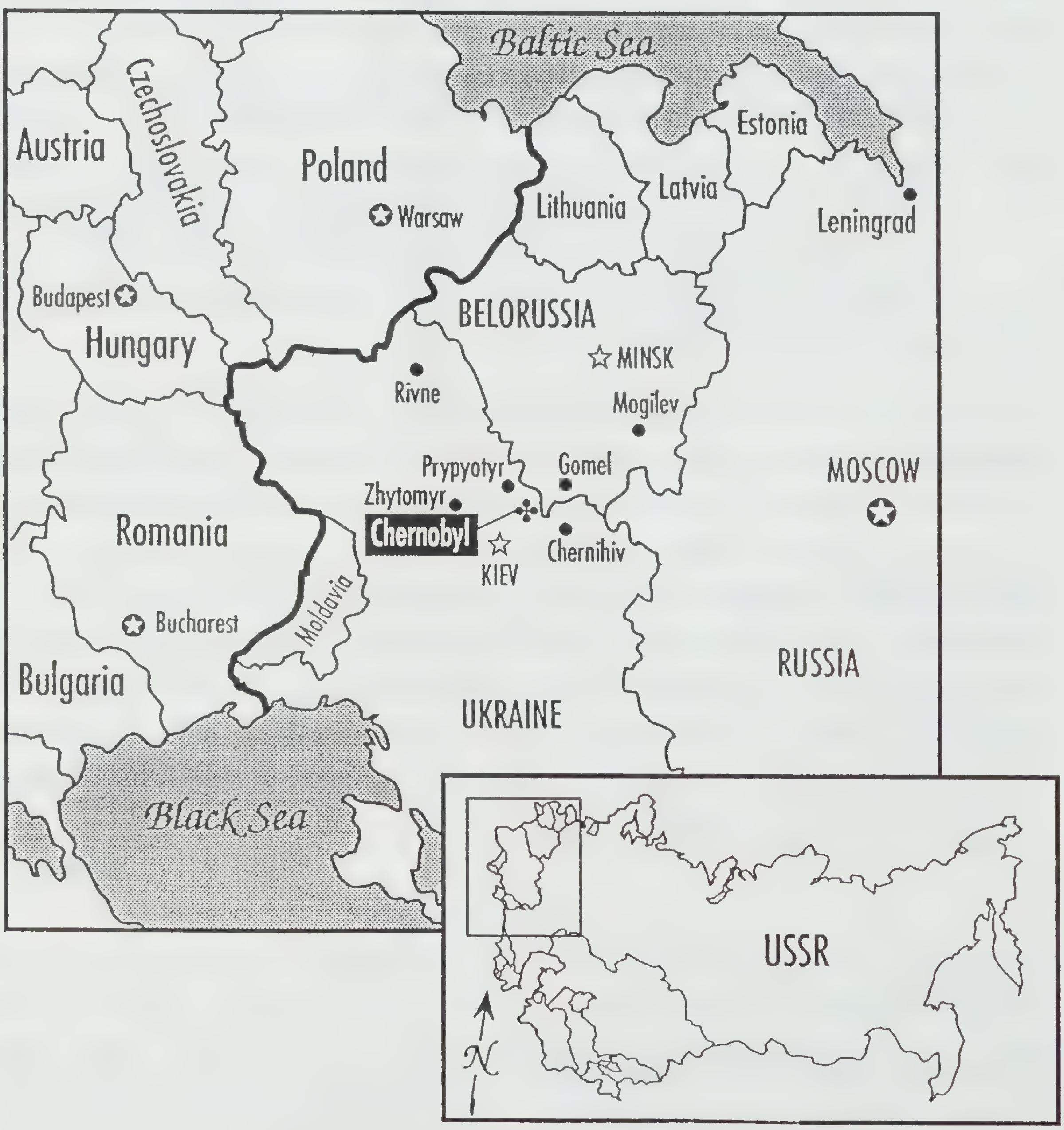
As noted earlier, the power plant at Chernobyl was equipped with boiling-water pressure tube reactors termed RBMKs. Fifteen RBMK-1000 plants like those at

Chernobyl, each generating 1,000 megawatts of electricity, provide more than half of the Soviet Union's nuclear-generated electrical capacity.[42]

The Chernobyl site, with four completed reactors and two additional ones under construction, is located on the Pripyat River, approximately 24 km northwest of the town of Chernobyl and 110 km north of Kiev (Figure 1). The nearest town is Pripyat, which grew up around the power plant.[43] At the time of the accident, about 45,000 people lived within the immediate neighbourhood of the plant, and about 150,000 within 30 km.

FIGURE 1

Ukraine and Surrounding Areas



Source: D.R. Marples, "Chernobyl: Its effects in the USSR," Forum for Applied Research and Public Policy (Summer 1990): 7.

The following is a brief description of the main features of the RBMK reactor.

> The Chernobyl reactor was of a type referred to as RBMK in which the neutron-moderating material is graphite and the fuel is cooled by ordinary water (in CANDU reactors, heavy water is used for both these functions). In the RBMK design, steam is produced directly in the fuel cooling system, whereas the CANDU utilizes steam generators in which the heat removed from the fuel by the heavy water is used to boil ordinary water.
>
> In the Chernobyl reactors, much of the fuel cooling equipment is contained within leak-tight compartments which are intended to fulfill a function similar to that of the concrete containment buildings in which CANDU reactors are required to be housed. However, the reactor and the piping which exits above the top of the reactor are not contained in such a compartment.
>
> The RBMK design includes emergency protective mechanisms which are designed to shut the reactor down if a hazardous condition is detected. The rate of shutdown is rather slow, and the success of the protective action depends on supplementary action by control rods which normally are partially inserted into the reactor.
>
> The feature of the reactor which played an important part in the accident was a characteristic known in technical terms as a positive void coefficient of reactivity. This means that when the amount of steam (or void) in the reactor increases, there is a feedback effect which, if not controlled, will cause the power of the reactor to increase, and thereby further increase the void in the reactor.[44]

The Accident

The Atomic Energy Control Board of Canada prepared the following description of the events leading up to the accident. Table 2 summarizes the sequence of major events preceding the initial explosion.

> In the course of shutting down the reactor for routine maintenance, the operators were conducting a test to demonstrate that, after the steam supply to a turbine had been cut off, the mechanical energy of its rotor could be harnessed to supply electrical power to important equipment for about 50 seconds.

TABLE 2

EVENT SEQUENCE AT CHERNOBYL

TIME	EVENTS	COMMENTS
April 25		
01:00	Reactor at full power. Power reduction began.	As planned.
13:05	Reactor power 50%. All steam switched to one turbine.	As planned.
14:00	Reactor power stayed at 50% for 9 hours because of unexpected electrical demand.	
April 26		
00:28	In continuing the power rundown, the operator made an error which caused the power to drop to 30 MW(th), almost shutting the reactor off.	This caused the core to fill with water & allowed xenon (a neutron absorber) to build up, making it impossible to reach the planned test power.
01:00-01:20	The operator managed to raise power to 200 MW(th). He attempted to control the reactor manually, causing fluctuations in flow and temperature.	The RBMK design is unstable with the core filled with water -- i.e., small changes in flow or temperature can cause large power changes, and the capability of the emergency shutdown is badly weakened.
01:20	The operator blocked automatic reactor shutdown first on low water level, then on the loss of both turbines.	He was afraid that a shutdown would abort the test. Repeat tests were planned, if necessary, and he wanted to keep the reactor running to do these also.
01:23	The operator tripped the remaining turbine to start the test.	
01:23:40	Power began to rise rapidly.	The reduction in flow as the voltage dropped caused a large and fast increase in boiling leading to a fast power rise.
	The operator pushed the manual shutdown button.	Too late. The damage was done in the next four seconds. The emergency shutdown would have taken six seconds to be effective.
01:23:44	The reactor power reached about 100 times full power, fuel disintegrated, and excess steam pressure broke the pressure tubes.	The pressure in the reactor core blew the top shield off and broke all the remaining pressure tubes.

Source: V.G. Snell and J.Q. Howieson, Chernobyl - A Canadian Perspective (Mississauga: Atomic Energy of Canada Limited, December 1986), p. 9.

> While reducing power in preparation for this test, the operators made a simple error which caused the reactor power to be reduced to a low level, at which very little steam was being produced in the reactor. Under the conditions which existed at that point, the characteristics of the reactor made it difficult to re-establish the required power, and the test should have been aborted.
>
> In an effort to increase reactor power to a level at which the test could be performed, the operators committed several serious violations of the rules for safe operation of the reactor. In particular, they blocked several of the signals which could have initiated an emergency shutdown, and removed from the reactor most of the control rods which are required to supplement the emergency shutdown action. These violations seriously impaired the capability of the emergency shutdown equipment.
>
> The operators succeeded in restoring power to a level at which they believed they could conduct the test, although the condition of the reactor was still such that there was very little steam in the core. When the test was initiated, the flow of coolant in the reactor decreased and the rate of steam production began to increase. Because of the positive void coefficient of reactivity discussed above, the steam production produced a feedback effect which caused the reactor power to increase. The control system was unable to cope with this power increase, and under these conditions the emergency shutdown equipment could not act quickly enough to terminate it. The result was a rapid uncontrolled rise in reactor power which was terminated only when there was a violent explosion which destroyed the reactor.[45]

The steam pressure as the reactor went to between 100 and 500 times full power lifted a 1,000-ton cover plate, turned it on its side, and ripped open the reactor, leaving the hot core exposed to the environment.[46] A large initial release of radioactive material, which included fragments of the fuel, resulted. After this large, explosive release, the emissions from the damaged reactor fell to a low level.[47]

The first attempt to control the reactor after the accident was made by local personnel before the Moscow experts arrived. Their attempt to flood the damaged reactor failed because water passed through passages between the different reactors, threatening the integrity of the adjacent units (this is a small but important design flaw).[48] Later that day, it was realized that the graphite in the reactor was burning, and radioactivity

releases were increasing. Then, on April 27, 1986 and succeeding days, 5,000 tonnes of material was dropped by helicopter. This smothered the fire, but the heat of the radioactivity still kept the core hot and continued to evaporate fission products. Not until liquid nitrogen was introduced into passages below the core did it cool and the releases stop.[49]

Until this happened, heat from the decay of the residual fission products caused the temperature within the remaining core to rise to the point where fission products began to distill out of the reactor. Nine days after the initial accident, the daily release rate of radioactive material was nearly as high as it was at the time of the initial release.[50]

Since the emission of radioactive material from the reactor resulted from two important but different controlling processes, the release fraction of the core inventory of radionuclides varied substantially according to the volatility of each chemical element. Essentially, all of the noble gases, roughly half the volatile elements including iodine-131, isotopes of caesium (Cs-134, Cs-137), and only a small percentage of the refractory materials (those having high melting points) including isotopes of strontium (Sr-89, Sr-90), cerium (Ce-141, Ce-144), and plutonium (Pu-238, Pu-239, Pu-240) were released.[51] It should be noted that strontium-90 and caesium-137 are long-lived fission products.

After the accident, the initial plume dispersed to the northwest and reached Finland and Sweden. Early detection alerted the European nations to the occurrence of a major nuclear reactor accident, until then unannounced by the Soviets. Because the release occurred over many days under changing meteorological conditions, the overall trajectory of the plume was complex. Scandinavia, eastern Europe, and, at later times, southern Europe were most heavily affected.[52]

Following the initial response, the next step taken was to enclose the damaged Unit 4 in a sarcophagus to prevent any further radioactive releases. This was finished in October 1986. Massive new foundations were built by burrowing below the reactor, and heat exchangers were installed to allow the decay heat to be removed. Almost no radioactivity now escapes.[53] After Unit 4 was enclosed, decontamination of the others was undertaken with Units 1 and 2 being restarted in October and November, respectively. The sarcophagus built to contain the reactor core is now cracking.[54] A major issue in the Soviet Union is whether to build a new structure around the breached containment of the sarcophagus, or rather to first remove radioactive

materials from the core for underground burial. The high level of emotion associated with environmental issues in the USSR today has made this a highly-publicized, widely-debated issue.

While the Ukranian parliament voted in August 1990 to close the remainder of the Chernobyl power station,[55] the decision is yet to be reviewed by the Supreme Soviet.[56] Since the three functioning units contribute a substantial proportion of the energy supply of the Ukraine, it is uncertain where replacement electrical generation would come from.

Reasons for the Accident

In addition to the operator errors which were noted earlier, reviews of the Chernobyl accident have identified several major design features and management characteristics which appear to have contributed to the incident's occurrence and severity.[57]

Design shortcomings include:

- a slow and clumsy control rod system;
- a "positive void coefficient" which means that as water is lost to steam, the reaction speeds up leading to more water boiling and producing a positive feedback to encourage the reaction to speed up. This instability is particularly dangerous at low power;
- it appears that the design of the plant permitted the operators to easily disable several important parts of the reactor's safety system;
- the solid graphite moderator could not be rapidly displaced to terminate a power excursion. As well, once the graphite began to burn, it produced additional intense heat and an updraft of hot air which carried radionuclides far afield;
- the RBMK reactor has an inadequate containment system by world standards. No kind of containment surrounds the tube, control and refueling systems at the reactor's top, so if it lifts, radioactive and irradiated materials escape directly into the poorly-sealed building and hence into the environment;
- the design and operation of the RBMK reactor appears to place a very high reliance on correct operator action. While operation of all reactors depends on correct action by plant operators, most designs are much more tolerant of operating errors than is the Chernobyl design; and
- the RBMK reactors are not equipped with shutdown systems which are independent from the control system.

As well, management errors contributed greatly to the accident at Chernobyl. Examples include:

- while the RBMK's designers knew of its technical design shortcomings, and devised a set of operating rules to be rigidly followed, they seem to have made little attempt to educate the plant operators. Six important safety devices were deliberately disconnected on the night of April 25, and the reactor was deliberately and improperly run below 20% power. These incidents may not have occurred if the operators had understood the elementary physics of their reactors;[58] and

- the official line of the Soviet Academy of Sciences was that an accident such as Three Mile Island can only happen in a capitalist society where they put profits ahead of safety. While this was obviously a political viewpoint, there was a danger that professional safety people would believe it. The "it can't happen here" philosophy appears to have been widespread.[59]

In 1990, the Soviet Union has reopened the official inquiry into who should bear responsibility for the accident.[60] The original commission, set up immediately after the accident, placed the blame on operator error. Now, a new, independent commission convened by the State Committee for Industrial and Nuclear Power Safety is said to be preparing to consider whether the design of the RBMK reactor was itself inherently unsafe. Earlier claims that, until Chernobyl, the RBMK had an accident-free record are now reported by the State Committee for Nuclear Safety to be false. There apparently had been a "class three" ("serious") accident in the No. 1 reactor of the Leningrad station in November 1975.[61]

In a recent interview, the director of the Chernobyl plant described the many technical improvements and new safety systems which had been installed that are designed to prevent the type of accident which occurred in 1986.[62] He noted, however, that the days of the RBMK are numbered. A major problem has been the expansion of the graphite through radioactivity, which entails replacing the fuel channels at 15-year intervals. To alleviate this problem, a major technical modification is required, and this would extend the operating span of the reactor to the regular 30 years. The future, however, was said to lie with the VVER (water-pressurized) reactor type, moderated by helium.

Radiation levels recorded in June 1989 indicated that at a distance of 300 m from the sarcophagus, the level was 1.2 millirems per hour, or about 160 times the natural background. Closer to the damaged reactor, the level was 1000 times normal.[63]

Local Impacts

In contrast to the Three Mile Island accident, significant escape of radiation occurred at Chernobyl. While the health effects of high doses of radiation are fairly well known, the long-term impacts of low-level radiation exposure are more speculative, since predictive methods involve extrapolation of the health effects of people exposed to various levels of radiation at Hiroshima and Nagasaki. In other words, effects are predicted on the basis of probability. The difficulty of assigning those Japanese victims to specific exposure categories means that there is considerable uncertainty and debate about the health effects of low-level radiation exposures in professional public health circles.

A study of the health impact of the Chernobyl accident[64] indicated that no acute effects have occurred outside the Soviet Union, where 237 cases of acute radiation sickness, including 31 deaths (as of 1988), were reported.

Those workers and populace in the 30-km zone surrounding Chernobyl may experience some detectable increase in health effects in the years to come. Given present early data, a doubling of leukemia risk was be expected for the period 1988-1989. Some possibility also exists of a few added cases of severe mental retardation in recent children of this exposed group. No adverse genetic effects were predicted to be observed in the entire group.[65]

Those near the site who experienced acute radiation sickness have increased risk of leukemia and other forms of cancer, depending on the type of exposure pathway and the degree of exposure.[66] A Soviet helicopter pilot, who made four flights in five days over the plant through radioactive gases to dump materials, recently underwent a bone marrow transplant in Seattle to combat leukemia and subsequently died.[67]

Other reports have suggested that 2,000 soldiers consigned to duty in the 30-km exclusion zone for over two years were allowed to absorb more radiation than the civilians they worked alongside. As well, a hunger strike by sick rescue workers from the Chernobyl zone was reported, in which they were protesting against hospital officials who refused to admit a link between their illness and the radiation from the accident.[68]

Some measures which have been instituted suggest that the scale of the contamination may be worse than first thought.[69] Mikhail Gorbachev is reported to have ordered that holidays should be offered to all children that need them, away from the areas contaminated by the fallout from the accident four years ago. A special health farm is to be set up, because following the incident, children in the settlements near the plant have not been able to play outside at all, causing physical and emotional deterioration.

Cleaning efforts concentrated on the 30-km inner zone, which is now fit for the cultivation of crops in greenhouses as near as 3 km from the plant. But outside the zone, there are still a few "hot spots" where contamination by caesium-137, one of the longer-lasting isotopes, is excessive.[70] Maps showing the extent of contamination are still incomplete. So far, only caesium fallout has been documented, and maps of strontium-90 contamination are to be published later in 1990.

Some reports have suggested that studies to date have not taken into account illnesses other than those directly attributable to radiation. One medical researcher from Minsk in Byelorussia, which received some 70% of the fallout, reported that the incidence of tuberculosis has risen by 14% since the accident, and suggested that ruthenium affects the lungs, weakening their resistance to infection. In southern Byelorussia, between 50 and 70% of children are now said to have health problems, with about 8% having thyroid complications in forms not observed prior to Chernobyl. The incidences of cancers and of congenital deformities was said to be significantly higher, while common illnesses were reported to have become up to 70% more frequent because people's immune systems had been weakened by radiation exposure.[71]

Just how much radiation the population of Byelorussia actually received is difficult to determine due to a shortage of instruments and poor methodologies.[72] Some researchers have estimated that one-fifth of the children had received 10 gray or more since the accident. This was described as 10 times as much as would be needed to cause illness and about 100,000 times as much as people normally encounter in a year from background radiation.

Realizing they underestimated the extent of damage from the accident, Soviet officials have announced that 14,000 more people will be moved from the area in 1990.[73] Pravda said radioactive dust that has piled up in the exclusion zone around the plant will take decades to remove and will have to be processed by a special, as yet unbuilt, complex.

Soviet reports indicate that 32 districts in six regions of the Ukraine are affected by radiation to varying degrees, with nearly 60,000 people living in the area that is strictly monitored.[74] Furthermore, in the territory with radiation levels above five curies, there are more than 200,000 inhabitants. This area includes districts more than 54 km from Chernobyl. Ninety thousand people have been moved from their homes in the years after the accident, apparently in addition to the 100,000 who were taken out of the exclusion zone a few days after the accident. The Pravda report indicated that the events at Chernobyl contaminated 4.9 million hectares in the Ukraine, of which about two-thirds was agricultural land. This did not include areas of neighbouring Byelorussia, where an estimated 20% of that republic was contaminated.[75]

Three regions of Byelorussia that are severely affected by fallout are to be made into a reserve where scientists will study the effects of radiation on wildlife.[76] According to Tass, some 1,000 hectares of forest, up to 7 km from the reactor, are expected to die. Mutations are already reported to be appearing in vegetation on the edge of the dying forest, with some pine trees having needles 10 times as big as normal, and oak and acacia trees having sprouted huge leaves.

Surveys have recorded high counts of radioactivity on the beds of reservoirs as well as in fish, water insects, hedgehogs, shrews, voles and waterfowl. Some rodents have been reported to show genetic abnormalities.[77] One scientist who has been studying the badly-affected Narodichi district of Zhitomir province in the Ukraine said that gross abnormalities are appearing in cows and pigs, and noted that "undoubtedly this region is greatly contaminated with strontium-90." However, these anecdotal accounts of severe malformations of local flora and fauna do not accord with what is known of the after-effects of the Hiroshima and Nagasaki explosions.[78]

There has been some concern that, in spite of a much greater degree of candor than was evident in the past, the Soviet authorities have not reported honestly the number of deaths resulting from the accident at Chernobyl.[79] In summer, 1986, the death toll was officially fixed at 31 where it remains. Two probable victims omitted from the list are: Valerii Legasov, who led the Soviet delegation to the Post-Accident Review Conference in Vienna in 1986, and who committed suicide two years and a day after the accident; and Volodymyr Shevchenko, who made a documentary film about the struggle to bring the reactor under control. He died a few months later.

One recent article described a first-hand account by a Soviet journalist of events in the Ukraine at the time of the accident. The author noted that while the rest of the world was alert, in despair, full of alarm, the population of Kiev - only 80 km from Chernobyl - was absolutely at ease, and unaware of the disaster.[80] The populace did not learn of the accident for eight days, and thus took no steps to minimize possible exposure to fallout. Even the reports prepared by the Soviets for presentation to United Nations agencies in Vienna and elsewhere were said to have been immediately classified, and thus were largely unavailable to the Soviet public and even the USSR's academics.[81]

In terms of social impacts, most of the houses and other structures in the 30-km exclusion zone will likely be demolished and trees planted.[82] Some elderly farmers have been permitted to return to and remain in the area which is the least contaminated portion of the zone.[83] The loss of thousands of hectares of some of the most productive farm land in the Soviet Union is another cost which citizens will have to bear. The Ukraine Republic comprises less than 3% of the USSR but produces 23% of its food.[84]

Other local and regional impacts include the cost of constructing a new city (Slavotich) 60 km from Chernobyl, and costs of relocating plant workers. Chernobyl's major impacts, at both the local and global levels, could well be economic and psychological, with plant workers, their families and the general population intensely anxious about the dangers of radiation.[85]

Because of the great expense incurred, the government of the Byelorussian SSR has independently appealed to the international community, through the United Nations' Economic and Social Council, for all possible assistance.[86] Byelorussian representatives indicated that an area populated by 2.2 million residents had been contaminated by radioactive fallout and the Republic has essentially lost 20% of its farmland. Dozens of settlements have ceased to exist due to evacuation of residents to uncontaminated areas and new spots of radioactive fallout deposition are still being discovered. More than 100,000 people were said to still be living in the areas with caesium-137 contamination densities over 15 curies per square kilometre.

The estimated expenditures required under the latest version of the Byelorussian Republic's State Program for Eliminating the Consequences of the Chernobyl Accident are 17 billion rubles (almost two annual budgets of the BSSR) including 12.8

billion rubles of capital investments. A comparable figure for the Ukraine was said to be another 17 billion rubles.[87]

Potential Impacts to the USSR

The Chernobyl nuclear accident has had impacts throughout the USSR as well as at the international and global levels.

According to Dr. Robert P. Gale, an American physician who played a major role in the international medical assistance which was provided to the Soviet Union following the accident, the most important aspect of Chernobyl to date is the role it plays in Soviet politics.

> Chernobyl is a rallying point for several political constituencies including environmentalists, persons concerned with the impact of technology on society, policy planners responsible for energy development within the Soviet Union, and, to a lesser extent, Ukrainian nationalists. Representatives from each of these constituencies have campaigned on platforms relating to various aspects of the Chernobyl accident and have recently been elected to the Soviet Congress of Deputies. Because these persons have political alliances to which they must respond, it is important to carefully weigh their statements concerning the consequences of the Chernobyl accident.[88]

The economic cost to the Soviet Union of the accident is still not fully calculated. It has been reported that there was a direct cost of about $6.8 billion relating to loss of the reactor, relocations, medical care and decontamination, along with an equal amount for indirect costs, such as replacement of lost power, new construction and food surveillance. With additional costs within other countries, the total may be about $15 billion.[89] One Soviet parliamentarian estimated the USSR would need about $380 billion over the next 10 years to deal with the consequences of Chernobyl.[90]

In terms of human health, Anspaugh *et al.* (1988), on the basis of a large amount of environmental data and new integrated dose assessment and risk models, calculated the collective dose commitment to the approximately three billion inhabitants of the Northern Hemisphere to be 930,000 person-gray, with 97% in the western Soviet Union and Europe.[91]

Their best estimates for the lifetime expectation of fatal radiogenic cancer would increase the risk from 0 to 0.02% in Europe and from 0 to 0.003% in the Northern Hemisphere. In other words, one might project up to about 17 thousand additional fatal cancers caused by radiation in Europe, where some 123 million are normally expected, an increment of about 0.01%.[92] Since these estimates are derived from increments in a probability distribution, they are not certain, and the authors did not rule out zero increased cancers as a possibility. Probably, in reality, no adverse health effects will be **identifiable** by studies of the populations in the remainder of the Soviet Union or abroad. This would apply to cancers as well as other adverse health effects such as severe mental retardation or genetic disorders, where the incidences are said to be expected to be so low as to be unobservable, compared to natural or spontaneous incidence.[93] Estimates of health effects as well as social and economic impacts based on such predictions are considered by the authors to be reasonable but early projections. As such, their evaluation and, where possible, validation in highly-exposed populations and the environment will require study for some period of years.

Robert Gale has noted[94] that the Byelorussian government has used a stricter standard than is conventionally used internationally as a basis for evacuation planning, so it is difficult to assess whether the extent of the evacuations is justified. Dr. Gale reported that an increased incidence of radiation concerns will be detectable only within the proximate exposed population which includes about 800,000 persons now residing in the Soviet Union. The current plan is to follow their health annually, although whether this can be done within the unstable political and economic framework of the present Soviet Union may be uncertain.

Dr. Gale's characterization of the radiation-related health impacts follows:

> In summary, there are likely to be long-term health consequences of the Chernobyl accident, particularly an increased incidence of cancer. However, it is not possible to accurately predict their magnitude. These same reservations apply to predictions of teratogenic affects and genetic abnormalities as a consequence of the accident. Unless a careful epidemiology study/surveillance program is performed, it may not be possible to detect these effects. It is also possible that their magnitude may be sufficiently low that other changes in cancer-related risk factors, such as cigarette smoking or diet, will obscure the accident's effects.[95]

Certainly, there was widespread concern in many countries regarding the potential effects of radioactive fallout from Chernobyl. Deposition from the radioactive plume was measured in Germany,[96] France,[97] Japan,[98] eastern Europe,[99] and elsewhere. These ground deposits exceeded health guidelines for protective action in communities as far as 2,000 km from Chernobyl.[100]

In the USSR, major regulatory changes are underway to revamp the nuclear plant licensing process and reorganize the entire nuclear program,[101] including for the first time, public involvement. Elsewhere in the Soviet Union, local opposition to proposed and existing nuclear plants has increased.[102] The accident has served a role in unmasking institutional weaknesses in the country's management of complex technologies.

International Impacts

Increasing scepticism regarding nuclear power has been reported in Britain, Greece, Italy, Finland, the Netherlands, Hungary and West Germany. However, although the growth of public opposition to nuclear power was followed by some softening of opposition by 1987, some reports suggest that in no nation has opposition declined to its pre-Chernobyl level.[103]

For a substantial part of Europe's agricultural community, Chernobyl was not a distant, abstract event but one that demanded temporary and, sometimes, long-term changes in lifestyle and livelihood.[104] Since a potential pathway of radiation exposure for humans is through consumption of contaminated meats, milk and produce, many farmers throughout Europe were immediately and dramatically affected by government intervention to control contamination, as well as public caution based on news reports.

Lofstedt and White have recently summarized a number of such cases.[105] Examples include:

- in West Germany, dairy cattle were removed from pastures contaminated with iodine-isotope fallout throughout a substantial area surrounding Lake Konstanz. Since then, dietary adjustments by many consumers in response to the fallout have intensified and extended the economic jolt felt by West German farmers;

- deposition of caesium-137 in the Cumbrian Mountains of northern England resulted in an initial three-week ban on the movement or slaughter of four million sheep on 7,000 farms. The ban was soon extended indefinitely, and a substantial number of farms are still affected; and

- the Saami people of northern Sweden, with about 2,500 active herdsmen overseeing 275,000 reindeer, depend on their herds for their own meat consumption and as a cash crop exported to the urban centres of southern Sweden. A substantial proportion of the reindeer were declared contaminated and unfit for human consumption. Even when the meat became "safe" again, public demand for reindeer was diminished greatly, placing severe economic and social strain on the Saami, who are now much more dependent on government subsidies and welfare.

In the United Kingdom, studies are now underway to see if adding minerals to the land could reduce the amount of radioactive caesium taken up by vegetation.[106] Because of the continuing presence of radioactive hotspots on fells grazed by sheep in north Wales, southwest Scotland and Ulster, government restrictions remain in force on the movement and slaughter of animals in the most affected areas.

Since Chernobyl, the British government has spent £4 million on research on caesium-137 on peaty upland soils, and £7 million to compensate farmers for lost income from lamb sales.[107]

The economies and environments of other European nations stretching from Norway to France were affected by Chernobyl.[108] In Switzerland fishing was banned, perhaps indefinitely, when caesium concentrations in fish and lake sediments became elevated. The reindeer economy of the Norwegian Laplanders has been undermined for up to seven years, while in Austria there was significant contamination of grasslands, requiring the purchase of other fodder. Greece was forced to suspend the production of sheep and goat cheese. Significant impacts on lamb, mutton and cattle production were experienced throughout Scandinavia.

Only time may tell what the ultimate impact of Chernobyl has been on human health and the environment. The number of infant deaths in southern Germany was significantly higher than expected in the months following the accident, although further investigations will be needed to confirm or refute an association between early infant mortality and radioactive fallout from Chernobyl.[109] A prominent epidemiologist in Britain noted that "These are the first lot of tentative but disturbing findings" that the accident at Chernobyl adversely affected health.[110]

Whether or not radiation from Chernobyl actually does result in direct health problems or environmental damage outside the Ukraine and Byelorussia, it is clear that significant economic impacts have occurred in many European regions, and that fear and stress and their effects are widespread. Cleanup and mitigation costs in the USSR will have an enormous impact on the Soviet economy. Concerns raised by the accident will also be an important factor in determining future nuclear energy policies in that country.

Much of the discussion on nuclear accidents centres on the human costs, but the Chernobyl accident has shown that the direct impact on other resources, particularly agriculture, can also be severe.[111] The aggregate effect of such an accident is extremely large and unpredictable. As the western European experience shows, costs are not insignificant even if the impact on human health is minimal. Furthermore, the costs incurred depend on the policies adopted and the degree of coordination and pre-planning involved.

Many countries have reviewed their own nuclear industries following Chernobyl, to identify whether any features of that disaster might provide lessons for future operation of commercial power plants abroad. It can safely be said that almost no industrialized country was untouched by the accident at Chernobyl.

THREE MILE ISLAND & CHERNOBYL: SOME COMMON FEATURES

While these two accidents were dissimilar in many ways, particularly in their release of radioactivity, consideration of points in common which may have contributed to these incidents is instructive.

John F. Ahearne, Chairman of the U.S. Department of Energy's Advisory Committee on Nuclear Facility Safety, undertook such a comparison following the accident at Chernobyl. Dr. Ahearne has extensive experience in the scientific and regulatory aspects of nuclear power, and was an invited witness for hearings of Ontario's Select Committee on Energy during its review of Ontario Hydro's Demand/Supply Planning Strategy in 1988.[112] At these hearings, Dr. Ahearne provided a comparison of Canada's nuclear power industry with those in the United States and other countries, so that he is particularly well qualified to compare the Chernobyl and Three Mile Island reactor accidents.

Dr. Ahearne reported several similarities in these two accidents:[113]

- In both cases the accidents occurred in the early morning, about 4 a.m. at TMI and a little after 1 a.m. in the Ukraine. These are typically slow periods on shifts.

- Both reactors are very sensitive to perturbations in the system; the positive void coefficient makes the RBMK extremely sensitive, while the TMI Babcock & Wilcox design has a once-through cooling system with a small volume of water compared with other U.S. reactors, and is said to be well-known in the U.S. nuclear industry as being more responsive to perturbations than other U.S. designs.

- Complacency among operators, utilities, vendors, regulators and government oversight committees was evident in both countries. Neither country's nuclear industry believed that a major accident was possible.

- The Chernobyl operators did not pay attention to warnings from various sensors. TMI operators did not believe temperature readings that indicated steam was exiting through a stuck-open valve.

- In each case, the operators took a series of steps that were deliberate and that defeated the safety systems.

- The operators at Chernobyl had no simulator training for the accident sequence that occurred. Similarly, TMI operators had never trained for the sequence of the stuck-open valve, and instructions on how to handle such an event were not written in their emergency procedures.

- Both the TMI and Chernobyl accident reviews found weaknesses in the approval of operating procedures. In neither case were plant safety committees standard before the accidents, and there was no such input into reviewing and revising operating procedures.

- In each case, the operators did not understand their plant's engineering or basic nuclear processes. In other words, the operating staff had insufficient familiarity with the special features of the processes in a nuclear reactor to maintain sufficient feeling for the hazards involved.

It is significant to note that a number of the aspects of the accidents which Ahearne felt contributed to their occurrence and severity, are related to personnel factors and procedures, rather than to hardware deficiencies. While all reactor types have design features which need particular care during operation, the themes of complacency, failure to anticipate potential accidents and simulate them during training, and poor understanding of the reactors and nuclear processes by operators run prominently through the accounts of these major accidents. Clearly, these are management deficiencies rather than technical shortcomings, and of the factors noted above,

perhaps complacency is the most insidious and threatening to any application of technology, from power workshop tools to nuclear reactors.

OTHER EXAMPLES OF NUCLEAR ACCIDENTS

NRX Reactor - Chalk River, Ontario (1952)[114]

An accident that occurred at the NRX reactor (an experimental model from which the CANDU eventually evolved) was in some ways similar to the Chernobyl accident, although on a very much smaller scale and without injuries. The damage was not as severe, and when the core had been replaced, the reactor returned to service. The causes were determined to be operator errors in incapacitating the shut-down rods, which were followed by a rise in power to which they could not react. The operators then manually fired another shut-down mechanism which quickly drained the heavy-water moderator, but this was too late to prevent damage to the reactor core.

Lessons learned which were directed toward the design of CANDU reactors were described by Atomic Energy of Canada Limited to be:

- keep the control and shutdown systems independent;
- keep the mechanical design simple and powerful; and
- ensure the shutdown systems can be tested on-power to meet stringent reliability targets.

A serious accident also took place at the NRU research reactor at Chalk River in the 1950s. Less serious accidents, due to failure in pressure tubes, occurred at Pickering (1983) and Bruce (1986). There have been no fatal casualties at Canadian reactors as a result of nuclear accidents, and workers exposed to high radiation doses at NRX and NRU show no increased cancer mortality.[115]

West Germany (1977)[116]

An over-pressure accident at the Gundremmingen boiling-water reactor damaged pressure-relief safety valves and contaminated the reactor building or the containment chamber, causing the plant to be closed down.

West Germany (1987)[117]

A "top-level" accident took place at a pressurized-water reactor near Biblis in December 1987 but there was no public disclosure until 1988. The accident released only small amounts of radiation but it reportedly could have been worse. The operators made mistakes that allowed radioactive steam at high pressure into an emergency cooling circuit designed to take steam at low pressure. Before the accident, the operators had failed for 15 hours to notice a light warning them of an open valve between the primary and emergency cooling systems. When they noticed the light, they tried to close the valve by opening another to reduce the pressure on the first valve. This released steam and small amounts of radioactivity. Attempts to close the valve eventually succeeded. There was no rupture of pipework and normal operation of the reactor continued.

Windscale (Sellafield), United Kingdom (1957)[118]

The world's first major nuclear accident appears to have been a fire at a plutonium separation facility in northwest Britain. A fire developed in the graphite moderator of a gas-cooled reactor used to produce fuel for nuclear weapons. The plant, which was not a commercial power reactor for generation of electricity, was largely destroyed. Over 20,000 curies of iodine were released into the atmosphere, compared with 30 curies at TMI. A detailed inquiry into the accident revealed that the fire, which burned for a considerable period of time before it was detected, was the result of both major design faults and lack of experience among technical staff. The Chairman of Britain's Atomic Energy Authority at the time recently noted that the accident had "all the hallmarks of an industry in a hurry" but added that "one should not judge what happened 30 years ago in the light of what we now know."

Sellafield, United Kingdom (1986)[119]

The Windscale plant was subsequently redeveloped under the name of the Sellafield reprocessing plant, and comprises a number of facilities for storing and reprocessing spent fuel from nuclear reactors. Leaks of radioactive water from fuel storage sites became a serious problem in the 1970s when, in one case, 100,000 curies of radioactivity escaped into the ground over a number of years. Leaks were also reported in 1985-86. In February 1986, an "amber alert" took place in a 20-year-old chemical separation plant when, during maintenance on a pump unit used to sample

plutonium nitrate, a valve failed. A mist of plutonium was released and the plant was shut down for 15 hours. Around 50 microcuries of radioactivity escaped into the atmosphere outside the plant. Of the 71 workers evacuated, two were later found to be slightly contaminated. It should be noted that Sellafield is not a nuclear power station, but a facility to reprocess spent fuel from Britain's civil nuclear power stations.

Kyshtym (Kasli), USSR (1957)

An explosion took place in a high-level nuclear waste dump at a weapons production plant in the Ural Mountains which released a total amount of radioactivity in the same order of magnitude as that which resulted from the Chernobyl accident.[120] While the accident was kept secret for 30 years, and earlier "glasnost-era" reports indicated 2 million curies of radiation had been released and several hundred square kilometres contaminated,[121] later information revealed that 20 million curries were released into the atmosphere, and 15,000 square kilometres had been contaminated by fallout, primarily in the form of the long-lived radionuclide strontium-90.

The accident involved a chemical explosion in a tank containing radioactive waste.[122] There were said to have been no casualties, but 600 people were removed from the most heavily-affected zone over the succeeding week and, over the next eight to 22 months, the remaining 9,500 inhabitants of the region were evacuated, as the radiation threat became increasingly apparent.[123]

Once again, this accident was not at a commercial nuclear power station, but rather a military nuclear waste disposal facility.

National Reactor Testing Station, Idaho, USA (1961)[124]

Servicemen working on a three-megawatt boiling-water reactor are reported to have caused the control rods to be lifted out of the core. This made the reactor go supercritical and led to a melting of fuel. The debris from a resultant steam explosion killed three workers, although the radiation levels to which they were exposed have been described as fatal in any event.

Enrico Fermi Breeder Reactor, Michigan, USA (1966)[125]

An accident at this plant has been reported to have resulted in a partial meltdown. The 200-megawatt reactor, 30 miles south of Detroit, was a demonstration facility backed

by the US Atomic Energy Commission.

AEC Reactor, Los Angeles, USA (1959)[126]

The fuel elements in another, smaller Atomic Energy Commission reactor, located just outside Los Angeles, melted during an accident involving loss of coolant.

Hanford Nuclear Reservation, Washington State, USA (1944-1966)

Although not an "accident" in the sense that other events discussed in this section were, "serious" exposures to radiation were experienced by the public in the vicinity of the Hanford facilities.[127] More than 400,000 curies of radioactive isotopes were released secretly into the atmosphere between 1944 and 1947 during the reprocessing of uranium, when radioactive fuel rods were dissolved in acid to extract plutonium for use in nuclear weapons. As well, residents who drank water and ate fish from the Columbia River were exposed to radiation when eight of Hanford's nine nuclear fuel production reactors discharged radioactive cooling water between 1964 and 1966.

Initial studies to assess doses received by the public suggest that, from the airborne incidents alone, about 5% of the 270,000 residents living in the vicinity of the plant may have received "significant" doses of radiation, largely from ingesting contaminated dairy products. Studies are now underway to assess possible health impacts, particularly in terms of thyroid disease.[128]

The Hanford Nuclear Reservation has also been used as a depository for a wide range of nuclear wastes, including millions of gallons of highly radioactive liquid wastes generated from the processing of plutonium for use in nuclear weapons.[129] Concerns have been expressed about leaks of liquid wastes, steam explosions, and the potential for explosions due to gases, largely hydrogen, which form in the storage tanks. This situation is of particular interest to Canadians since the Hanford site is close to the border with British Columbia.[130]

Summary

This list of incidents is not intended to be complete or comprehensive, but to give a sense of the types of significant accidents which have occurred in the life of the nuclear industry. It is noteworthy that military facilities such as Windscale and Kyshtym were responsible for the greatest releases of radioactivity to the environment

prior to Chernobyl, and that security and secrecy requirements may have affected responses to these accidents and dissemination of information, both to the public, and also to other nuclear programs which would have benefitted from these experiences.[131]

Considering the number of American nuclear facilities, including power plants, which are near the Canadian border, it is particularly important that federal and provincial emergency response planners consider the distance that fallout from the Chernobyl accident travelled, with subsequent impacts on agriculture and other economic and social factors.

A recent review by John Ahearne, of safety standards at US military nuclear weapons plants run by the Department of Energy (DOE), identified numerous shortcomings with the defence program facilities and procedures.[132] Dr. Ahearne[133] noted that:

> The mishaps with the P-reactor showed just how far practices in the defense reactor program have diverged from those in the commercial nuclear industry. The accident at Three Mile Island taught utilities that the unexpected could occur and led to major improvements in operating practices and training, instrumentation, accident analysis, and maintenance. But the veil of secrecy surrounding the weapons program prevented these changes from becoming part of the DOE knowledge base.
>
> For example, Louis Roddis was surprised to find that the post-TMI emphasis on preventing hydrogen explosions had not led Hanford engineers to incorporate this phenomenon into their analyses. Dennis Wildinson, another member of the N-reactor review panel and the first president of the Institute of Nuclear Power Operations, a group set up to improve nuclear industry performance following TMI, wrote, "There is an apparent sense of complacency at many levels from the DOE staff on down through contractor operations personnel that 'It can't happen here' at the N-reactor. The major lesson from TMI-2 and Chernobyl-4 is that accidents can happen."
>
> This isolation was illustrated last year, when a well-known nuclear-safety expert met with nuclear-safety staff of a DOE contractor. The expert wondered why he did not recognize any of the employees from national and international meetings.

> The staff members told him that they did not attend those meetings because they could learn nothing from them. The employees seemed unaware that a gap had grown between their practices and those of their colleagues in the commercial nuclear industry.
>
> The gap means that safety analyses like those the Nuclear Regulatory Commission requires for commercial reactors have been done poorly or are out of date.[134]

Dr. Ahearne's main conclusion was that isolation breeds complacency. While this is currently true of military nuclear facilities, isolation from American nuclear data has been cited as a contributing factor in the British Windscale accident, when competing national goals limited the exchange of information. Political and ideological isolation may have contributed to the Soviet nuclear accidents at Kyshtym and Chernobyl, where western experiences, including lessons learned from Three Mile Island, were unknown or thought to be irrelevant in a non-capitalist environment.

In summary, it appears that the only accident in a commercial, non-military nuclear power station which has released significant radiation to the external environment is that at Chernobyl. That example, however, is extreme. In terms of dispersal of caesium-137, a nuclide with great biological significance, the Chernobyl release was equal to that of a very large nuclear bomb, in the 20 megaton range.[135] Even at 1,500 km, fallout in some places far exceeded the levels recorded during the period of atmospheric nuclear weapons testing.[136] Recent news reports indicate that the situation in Byelorussia may be even worse than originally thought, with the republic seeking international aid to help move one-fifth of its 10 million people from contaminated land.[137] The Chernobyl accident was a very significant event.

CANDU AND CHERNOBYL

Basic Designs

The CANDU and RBMK (Chernobyl) reactor designs are quite different in most respects. The CANDU reactor is fuelled by unenriched uranium oxide, moderated by heavy water and cooled by heavy water. The RBMK is fuelled with 2% enriched uranium oxide, moderated with graphite bricks, and cooled with ordinary "light"

water. The CANDU has an indirect steam cycle, while in the RBMK, steam from the reactor goes directly to the turbines. Table 3 lists the major design features of each design.[138]

It is beyond the scope of this paper to compare the two reactor designs in detail. Several reviews have done so.[139] Among the main practical differences are the following:

- the RBMK lacked the CANDU's massive confinement system;
- the RBMK cooling system involved much larger volumes of water capable of turning into steam than does CANDU. This underlay the massive structural damage at Chernobyl;
- the RBMK's moderator was flammable graphite whose burning carried aloft a large part of the radioactive debris and gases at Chernobyl; and
- the Chernobyl reactor was unable to achieve rapid shutdown following the power excursions whereas early failure of the calandria in CANDU accidents would lead to rapid shutdown.

Atomic Energy of Canada Limited has indicated that the severe accident at the NRX reactor at Chalk River in 1952, which largely resulted from an inability to shut down during a power rise, has led to a particular emphasis on shutdown capability in the design of the CANDU reactors in Canada. Contemporary designs have:[140]

- independent control and shutdown systems;
- simple and powerful mechanical design; and
- the capacity to test the shutdown systems on-power to meet reliability targets.

An ubiquitous statement[141] to the effect that "Canada's CANDU plants are North America's closest operating relatives to the reactor that exploded at Chernobyl" has often been attributed to an article in Technology Review by William Sweet.[142] In fact, that quote is an editorial headline and does not appear in the text of Mr. Sweet's article which deals with one very important similarity between the RBMK and the CANDU designs: the positive void coefficient. There are two other major design features which are common to the two reactor types. These are the use of pressure tubes instead of a single large pressure vessel as in most BWR and PWR designs, and the related ability of the RBMK and the CANDU to be fuelled while in operation. This on-line fuelling capability differs from other reactor designs in that the reactor

does not have to be shut down for refuelling, but fuel rods can be replaced continuously. The following sections describe these design similarities in more detail.

TABLE 3
COMPARISON OF CANDU 600 AND CHERNOBYL DESIGNS

FEATURE	CHERNOBYL	CANDU (typical)
Design		
Coolant	Ordinary water	Heavy water
Steam cycle	Direct (steam & water from reactor are separated and steam goes directly to turbines)	Indirect (hot water from reactor boils ordinary water in a boiler to steam, which then goes to the turbine)
Fuel	~2% enriched uranium oxide	Natural uranium oxide
Moderator	Graphite bricks (max. temp. 700°C)	Heavy water (max. temp. ~88°C)
Fuel channels	Vertical, pressure-tube, no calandria tube	Horizontal, pressure tube with calandria tube
Safety Systems		
Containment	No upper containment -- lower containment is concrete cells surrounding high pressure piping & connected to water pool, to reduce the building pressure.	Concrete building, or multi-unit negative pressure containment, surrounding all major piping, with water spray (dousing) to reduce the building pressure.
Shutdown	One mechanism: - absorber rods	Two complete systems: - absorber rods - liquid injection
	10 seconds to be effective	2 seconds to be effective
	Effectiveness depends on state of plant	Effectiveness independent of state of plant
Emergency Core Cooling	High pressure injection driven by gas and pumps, then pumped flow	High pressure injection driven by gas or pumps, then pumped flow

Source: V.G. Snell and J.Q. Howieson, Chernobyl - A Canadian Perspective (Mississauga: Atomic Energy of Canada Limited, December 1986), p. 16.

Positive Void Coefficient

The CANDU and RBMK reactors are the only operating commercial power plants which have a substantial positive void coefficient of reactivity.[143] This effect occurs when an increase of reactor void caused by coolant boiling leads to an increase in reactor reactivity (or power).[144] In the event of a loss of coolant accident in a CANDU reactor, the coolant in the pressure tubes will boil, creating steam voids. This will rapidly accelerate the chain reaction, requiring shutdown within two seconds. This is the positive void reactivity which the Hare Commission described as "one of CANDU's less desirable characteristics."[145]

The Chernobyl accident occurred because when certain tests were initiated, the flow of coolant in the reactor decreased and the rate of steam production began to increase. Because of the positive void coefficient of reactivity, the steam production produced a feedback effect which caused the reactor power to increase. The control system was unable to cope with this power increase, and under these conditions, the emergency shutdown equipment could not act quickly enough to terminate it. The result was a rapid, uncontrolled rise in reactor power which was terminated only when there was a violent explosion which destroyed the reactor.[146]

Other reactor designs, such as the US water-cooled plants, have the opposite effect: the power goes down as the boiling increases. Atomic Energy of Canada Limited (AECL) pointed out that this is not necessarily safer, but that it just means that there is a **different** accident where the power goes up.[147] For example, in a boiling-water reactor if the steam valves on the boilers close by mistake, the reactor starts behaving like a pressure cooker with the valve closed: the pressure rises and compresses the water, and since compression is the opposite effect to boiling, the power goes up. So BWRs must have shutdown systems to be able to handle this. AECL suggests that the general rule is quite simple: the shutdown systems must be powerful enough to overcome all sources of a power increase so as to shut the reactor down in an emergency. The larger the effect of boiling (whether positive or negative), the harder this is to do. It is better to have a small coefficient than a large one.[148]

The Atomic Energy Control Board (AECB) is the agency of the Government of Canada which controls the development, application and use of atomic energy. It exerts its authority by means of general regulations, regulatory policy statements and guides, and through licenses for specific facilities.[149] Noting the very important role played by the positive void coefficient of reactivity in the Chernobyl accident, AECB, in its analysis of the safety implications for CANDU reactors, came to the following conclusions:

> . . . CANDU reactors also have a positive void coefficient of reactivity, although the effect is smaller (by about a factor of 3) than in Chernobyl design when operating at low power levels. In the accident at Chernobyl, while the emergency shutdown system operated as designed, it was not designed to cope with the rapid increase in reactivity caused by the sudden increase in coolant void, and was therefore unable to act quickly enough to stop the increase in reactor power. If such an event, a rapid power increase with no effective shutdown system, were to occur in a CANDU reactor, the positive void coefficient could exacerbate the reactivity increase, and it is difficult to predict whether the reactor would shut itself down before power reached a level at which violent failure would occur. However, if a shutdown system operated as designed, it would terminate the reactivity increase and prevent serious consequences from occurring.
>
> All the commercial reactors in the world have ways of adding significant reactivity, regardless of whether the void coefficient is positive or negative, and therefore require shutdown systems to cope with accidents in which reactivity increases. The design of all reactors and their licensing requirements must ensure that shutdown systems can act quickly enough, and add sufficient negative reactivity, to overcome the maximum reactivity which can be added in an accident . . . .
>
> . . . The implications of the positive void coefficient of reactivity in CANDU reactors cannot therefore be considered in isolation, but must be examined together with the effectiveness of CANDU shutdown systems in coping with accidents in which the void reactivity is a factor.

. . . The safety analyses for CANDU reactors are required to demonstrate the effectiveness of each shutdown system in shutting the reactor down sufficiently quickly to mitigate the consequences of a wide range of accidents from any power level. These postulated accidents include events such as rupture of a large pipe in the main reactor cooling system, partial or total loss of circulating pumps, and failure of the reactor control system, all of which have the potential to produce a rapid increase in the volume of steam in the reactor and a consequent positive void coefficient. As a result of the above, the capability of the shutdown systems on CANDU reactors is required to be considerably greater than that of the emergency protective system at the Chernobyl reactor, particularly with respect to the speed at which they can shut down the reactor. Whereas the Chernobyl system was designed to insert negative reactivity at a rate of about 5 mk/s, a CANDU shutdown system can insert at least 24 mk in less than two seconds and for some designs the value is much higher.

Furthermore, the requirement that CANDU shutdown systems be fully independent from the reactor control systems means that their effectiveness must not depend on supplementary action by rods of the control system, as was the case at Chernobyl.

For those reactors which have two fully effective, reliable, and independent shutdown systems, the possibility that neither shutdown system would successfully shut down the reactor in an emergency situation is extremely remote. For this reason, the AECB accepts that complete failure to shut down in an accident does not need to be considered in the safety analyses of such reactors.

On the basis of the above, it is concluded that, for reactors which conform to current AECB licensing requirements, accidents similar to the one that occurred at Chernobyl are adequately protected against. The requirements for shutdown system design are adequate to ensure that a fast reactor shutdown will occur when required, even for those accidents in which the positive void coefficient of reactivity plays an important role.

> Nevertheless, the severity of the accident at Chernobyl would suggest that it would be prudent to re-examine the safety analyses of CANDU reactors, with particular attention to events in which a rapid increase in the volume of steam may occur, or in which there may be a rapid increase in reactivity, to confirm that the shutdown systems are indeed sufficiently effective. In addition, it appears appropriate to examine possible configurations of reactivity devices to ensure that it is not possible to put the reactor in an unusual configuration in which the shutdown systems might be rendered less than adequately effective.[150]

The AECB came to different conclusions for the four older reactors at Pickering "A" whose two shutdown mechanisms are not independent of each other and rely on common instrumentation. In view of the severity of the consequences of the Chernobyl accident, AECB concluded that it would be prudent to re-examine the safety of these reactors, particularly with respect to accidents involving failure of the reactor control system or loss of coolant accompanied by unavailability of the shutdown system.[151]

The latter case was independently simulated by Ontario Hydro and by Argonne National Laboratory in the United States at the request of the Hare Commission.[152] The results, which were very similar, indicated that a severe accident of this sort would damage the reactor, probably irreparably, and might cause unsafe conditions for the reactor operators and maintenance crews. But there would probably only be minor effects on the general public. The Commissioner expressed hope that the AECB would require such extreme-case analyses for all CANDU reactors.

The other possible accident sequence, involving simultaneous failure of the regulating system and failure to shut down at Pickering A, was not analysed by the Hare Commission, but its review concurred with the AECB recommendation that such a sequence should be analysed in the same way.[153]

The earlier AECL analysis of the Chernobyl accident concluded that no new processes or failure models had been revealed, and that Canadian design and operating practices

precluded the inadequacies of the Soviet RMBK reactors and its operators. Only the positive void reactivity coefficient was a common factor.[154] The Hare Commission noted[155] that, as the Ontario Hydro-Argonne analyses pointed out, the CANDU design **presumes** the need for highly-efficient, fully-computerized control systems, and also for a fast shutdown system or systems. Pickering A is the least well protected CANDU station in this respect, yet in its updated form, it appeared in the Commission's analyses, to be capable of containing almost all the released fission products except, as usual in such cases, the least damaging: the inert noble gases.

William Sweet, in his comparison of the CANDU and RBMK reactor designs,[156] cited Ontario Hydro vice president William Morrison as saying "Every reactor [design] has the potential for large reactivity increases, but only the RBMK did not recognize this adequately." In the same critique, Zig Damaretski, safety chief at AECB was reported to comment that the RBMK's shutdown system is satisfactory only when the reactor is at full power, but accident analyses seem to have assumed full power: an "almost incredible attitude."

On-line Fuelling

Like the RBMK, the CANDU is fuelled while operating in contrast to pressure vessel reactors in which the reactor must be shut down during the entire refuelling operation, thereby not producing electricity for an extended period. Unlike the RBMK, however, the CANDU is fuelled horizontally, so the rods do not penetrate the top, and the fuelling mechanism is encased in a formidable containment structure.[157]

At Chernobyl, the initial explosion brought down the heavy on-line refuelling gantry on top of the reactor, damaging the pipes of the emergency core-cooling system. This would not be the case if a similar event occurred in a CANDU reactor, because the fuelling mechanisms operate from the front and back of the reactor, so that they are not suspended above it.[158]

There may be safety advantages in dispersing the fuel among separated rods. Webb, in a comparison of western (non-CANDU) reactors with the RBMK made the following observations:

> The fuel rods in PWRs and BWRs are all bound together in a compact, large bundled mass of fuel rods (40,000 rods) inside a single vessel; whereas in

> the RBMK the fuel rods are separated in groups of 18 rods that are dispersed in a large block of graphite, which has very good heat conduction and dissipation properties. The bunching of fuel rods in the PWRs and BWRs thus concentrates the fuel to maximize the heat-up temperatures of a fuel melt-down, and consequently to maximize the potential for fuel boiling and vaporizing and releasing the fission products and plutonium. The fuel bunching also maximizes the potentials for a coherent interaction and mixing of a large mass of molten fuel and water, to produce the maximum potential steam explosion, which is about 200,000 pounds TNT equivalent for the PWR and BWR. Also, the single large vessel provides a source of ready water for such a steam explosion, which cannot be drained out in an emergency, as was the steam quench pond beneath the Chernobyl reactor.[159]

Because refuelling is possible without shutdown, the RBMK-1000 has recorded capacity factors of 80% or higher, which, with the CANDU, are among the highest in the industry.[160] (The term 'capacity factor' refers to the energy actually produced in a given year divided by the energy that would have been produced had the reactor operated at full power at all times).

Pressure Tubes

A final common major feature between the RBMK and the CANDU designs is the use of pressure tubes to contain the fuel. Most commercial power reactors use a single thick stainless steel pressure vessel to contain the entire core. CANDUs and RBMKs, however, contain the nuclear reaction within hundreds of fuel channels or pressure tubes. All contain fissioning fuel while the reactor is on stream, and all are connected to, and are hence part of, the primary heat transport system, which pumps hot, high-pressure water through the inner part of the channel to remove heat to the steam generators or turbines.[161]

One prominent nuclear engineer[162] pointed out that the use of many pressure tubes, rather than a single large pressure vessel as in PWR and BWR designs, may be a safety advantage. Should a catastrophic explosive rupture occur in a large pressure vessel, this would represent a single failure event for which there is no protection.

> The PWR and BWR containment are not designed to withstand a reactor vessel rupture. The 100-ton vessel closure dome could be blown 500 metres

> upwards by a vessel rupture, easily destroying the containment. Furthermore, such a dome blow-off could conceivably carry away the reactor's nuclear control rods, causing a severe runaway of the atomic reactions in the reactor core (due to the control rods being rapidly pulled out of the core), in addition to the tendency of the exploding reactor coolant to blow the core through the containment -- all of which are possibilities which have not yet even been investigated. The Chernobyl RBMK-type reactor uses no reactor pressure vessel, and thereby avoids such catastrophic potentialities.[163]

The use of pressure tube technology is not, however, without challenges. Following the accident at Chernobyl, one of the design modifications introduced to render the RBMKs less vulnerable to the type of accident thought to have destroyed Unit 4 was to make the control rod system faster.[164] According to one commentator, the speedier fuel rods could cause other serious problems related to the pressure tubes:

> Each RBMK pressure tube has a sensitive weld toward the top and bottom, which joins an inner zirconium-alloy section to outer steel sections. The Soviets were well aware that these welds were vulnerable to sudden temperature changes, according to Herbert Kouts, of Brookhaven National Laboratory, who believes one reason the RBMK had a slow control system was to avoid subjecting the welds to excessive thermal shock.
>
> If control rods were inserted suddenly, causing the temperature of the reactor to change abruptly, there is a serious danger that several of the tubes would rupture. A dozen or so breaks would easily suffice to lift the lid of the reactor, break the tubes and control mechanisms, and precipitate the chain of events that occurred the night of April 26.
>
> In fact, Richard Wilson of Harvard and some other experts believe that a multiple tube rupture might have actually caused the Chernobyl accident. In this scenario, the accident may have resulted when the operators subjected the reactor to thermal shocks as they sought to stabilize it at a low power level. Whether or not this actually happened, it could have happened. Wilson says that he and others have tried to get the Soviets to focus on this scenario, but the Westerners have had little apparent success.[165]

The Ontario Nuclear Safety Review examined pressure tube problems with Ontario Hydro's CANDU stations and noted that "the pressure tube technology has many advantages, but only if integrity of the tubes can be guaranteed through long working periods."[166] The review Commission describes the pressure tube problems as the "most serious" to have affected Ontario Hydro's power reactors.[167] The following is a summary of these pressure tube problems as presented by the Hare Commission:

> Leaks of heavy water from these tubes (into the fuel channel's annulus) have been detected 23 times since 1971, indicating that they were not performing as expected. These leaks were easily detected, so that defective tubes could be replaced. But on 1 August 1983, a pressure tube ruptured suddenly at Pickering A. Contaminated heavy water escaped into the reactor building. It was subsequently found that many tubes in units 1 and 2 were in poor condition. Between 1983 and 1988, the reactors were refitted with tubes made of a different alloy. Meanwhile, 1,030 MW of power were immobilized and had to be replaced. The work was performed well under awkward and hazardous conditions. Total costs will exceed $425 million, and collective radiation exposure to workers was over 7 Sv (well below prior estimates, but still high).
>
> A further pressure tube rupture occurred on 26 March 1986 at the Bruce A NGS, when the reactor was shut down. The surrounding calandria tube also ruptured. The consequences were less damaging than at Pickering A, but the event emphasized the seriousness of the problem.
>
> The cause of these failures is known to be formation within the zirconium, or at stressed points within and on its surface, of enclosures or blisters of zirconium deuteride (usually called hydride). This weakens the tube. Moreover, the extent of deformation of the tube due to the neutron bombardment, and to unplanned displacement of the garter springs separating it from the calandria tube, has been larger than predicted. A major research program is under way to find solutions.
>
> The Review's technical consultants agreed with Ontario Hydro and AECL that such pressure tube failures have serious economic consequences, but present little threat of radiative exposure of the public.
>
> If, however, there are major pressure tube failures in the future, there will certainly be a threat to the operational and maintenance crews in the reactor

> building, as well as a large refitting cost. And I am not convinced that there is no danger of public exposure, especially if the failure spreads to other fuel channels. Accordingly, maximum priority should be given to finding a solution, and to improved monitoring of the fuel channels, to avoid further surprises.[168]

A detailed consideration of the pressure tube problem in CANDU reactors is provided in the Hare Commission's Technical Report.[169] Of the two major recommendations made by the Commission, one related to pressure tubes:[170]

> Major Recommendation 2 - Integrity of Pressure Tubes
>
> That maximum and effective priority be given to finding a solution to the pressure tube problem, and to improved in-reactor monitoring. Investment in fuel channel research by Ontario Hydro should be increased, and greater emphasis given to the fundamental metallurgical problems, tapping expert knowledge available in other industries.

HUMAN FACTORS

In comparing the Chernobyl accident with Ontario's nuclear reactors, the Hare Commission remarked that at Chernobyl, "operational incompetence and neglect of regulations reached astonishing heights. Ontario Hydro's responsible and well-trained shift supervisors and operators would be unlikely to behave so ineptly."[171]

In earlier sections of this report which examined Three Mile Island, Chernobyl and other civilian and military nuclear accidents, the recurring human themes were isolation and complacency, both among plant operators and senior management. John Ahearne's comparison of TMI and Chernobyl[172] noted a lack of understanding of the basic physics of the reactors on the part of operating staffs and the failure of simulation training to anticipate the accidents which occurred. As well, senior management in both cases did not believe a serious accident **could** occur.

The Ontario Nuclear Safety Review considered many of these human factors in the operating systems of Ontario's nuclear reactors. Dr. Hare's comments are summarized below:

Ontario Hydro's reactors are designed and built by Ontario Hydro's own engineers and contracting staff, with input at the design stage from AECL. The process requires continuous interaction with AECB, which issues construction approvals and operating licences. AECB resident engineers are present at the station to provide continuing audit of the operating system.

The reactors are each under the direction of a Station Manager, who reports to the Nuclear Generation Division (NGD) at Ontario Hydro headquarters. The Station Manager is also directly responsible to AECB for all safety and licensing questions. In safety and radiological questions, the Station Manager is supported by specialized station staff and by various corporate groups at headquarters. The operating staff is organized by the Canadian Union of Public Employees, Local 1000, from the rank of Unit First Operator down. Union-management relationships in safety matters appear fairly satisfactory, but are not ideal: the 1985 dispute at Bruce came close to a confrontation (involving AECB) over the use of management personnel in operating positions. There are also complaints that worker safety suggestions are often disregarded.

Reviews of the operating system were carried out by an Operational Safety Review Team (OSART) from the International Atomic Energy Agency and by a consulting team drawn primarily from the oil and chemical industries. These reviews found the operating system sound, but isolated certain areas in which improvement was needed:

(i) There was a maintenance backlog at Pickering and Bruce because of inadequate staffing and resources (both reviews).

(ii) Conventional safety performance in NGD appeared inferior to that of the chemical industry. There had been no fatalities in 125 million person-hours, but NGD's temporary disability rate (although below its own target) was higher than the consultants considered acceptable (consultants).

(iii) Further developments in refresher training of operating staff were advised, as was periodic reauthorization by AECB (consultants).

(iv) Certain refinements in radiological protection were recommended (OSART).

> (v) There were some failures in communication between unionized staff and management (consultants).
>
> Ontario Hydro's response has been prompt and effective -- but has not yet met all the requirements.
>
> The system of basic training and qualification of reactor staff is excellent. Authorization of AECB is required for all positions with significant safety responsibility. Also excellent is the radiological training received and the principle that the individual staff member is responsible for his/her personal protection and has specified responsibility for the safety of others.
>
> Safety depends more on the quality and qualifications of the staff than on any other single factor. The CANDU stations are extensively computer-controlled, partly because of their complexity, and partly because of the need for instant response in the case of large LOCA. The operator's role is to audit this automated process. The obvious danger is boredom and inattention. Much depends on alertness to upset conditions (which are immediately announced in the control rooms) and on the skill with which the operators respond. So far, the record at Ontario Hydro's stations is good. Equally vital is the corporate safety imperative that lies behind it -- that senior management give safety its unstinted attention.[173]

In terms of training, licensing, and efforts at anticipating potential hazards, most of the lessons of Three Mile Island and Chernobyl appear not to have been lost on Ontario Hydro, the Atomic Energy Control Board, and Atomic Energy of Canada Limited. There does not appear to be isolation at the operation or management levels, and any complacency which exists is not overt.

A recent non-technical, popular article by David Lees[174] provided a rare, objective examination of nuclear power in Ontario which was reviled by pro- and anti-nuclear groups alike. Through interviews with operating staff at CANDU reactors as well as officials with Ontario Hydro, regulatory agencies and unions, he provided an interesting view of life working at a nuclear generating station.

Lees presents the first operator's job as being one of extreme high pressure and over-work due to a shortage of qualified personnel at that level. Indeed, his sources described the position as a "pressure cooker" to which many second operators do not aspire,[175] since it is high in stress and low on satisfaction. One first operator quoted

by Lees pointed out the presence of alienation between the station supervisor and his superiors (who are all engineers) and the operating staff.[176] The senior professional engineering staff are portrayed as technocrats rather than managers, with few skills in dealing with people.

Perhaps the most serious points noted by Lees in his article relate to an expressed strong feeling of apathy below the supervisory level of staff,[177] and a shortage of operating staff at nuclear stations, resulting in unnecessary safety oversights and delays in required maintenance.[178]

It is beyond the scope of this paper to assess the extent of such human factors at CANDU nuclear stations, but certainly there seems to be no cause for complacency. The Hare Commission noted several points relating to the management of Ontario's nuclear power plants, which, while not individually threatening safety, nevertheless suggest that an overhaul of operational safety culture would be in Ontario Hydro's and the public's interest:

> (i) The conventional safety record of the Nuclear Generation Division (NGD) of Ontario Hydro is good. Its record of no fatalities in 125 million person-years is outstanding. But the rate of temporary total disabilities and the target rate are higher than in the heavy chemical industry. The NGD bases its practices too exclusively on internal assessments of what can be achieved.
>
> (ii) Relations between Ontario Hydro and the Canadian Union of Public Employees Local 1000 have occasionally been soured by disputes.
>
> (iii) Control of technical maintenance at the stations seems fragmented, and backlogs appear too long.
>
> (iv) There are complaints that upward-directed safety recommendations are not always acted upon.
>
> (v) Self-audit practised among operational staff is not adequate; abnormal events or actions with no consequences are often not recorded.

(vi) There appear to be undesirable differences in safety systems and radiological performance between stations.

(vii) The organizational structure of the nuclear program appears excessively complex, with some ambiguities as regards responsibilities.

(viii) There is confusion in settling the status of temporary operating instructions at the stations.[179]

These factors led the Hare Commission to make another major recommendation:

> Major Recommendation 1 - The Human Element
>
> That Ontario Hydro:
>
> (i) ensure that, at an early date, its operational organization be thoroughly re-examined, in close cooperation with independent consultants who have international management experience;
>
> (ii) commission a study of factors affecting human performance throughout the utility, for the purpose of achieving optimum efficiency and the maintenance of high standards of safe operation;
>
> (iii) examine and revise its arrangements for establishing and maintaining an overall quality assurance program for each of its plants after taking advice from independent specialist consultants.[180]

Many of these initiatives are now underway. A director in the Nuclear Generating Division at Ontario Hydro has been reported as agreeing that, at a working level, the utility has been overmanaged and understaffed, but that changes are being made in response to reports from the Hare Commission and other studies of Hydro facilities based on a methodology developed by the Institute of Nuclear Power Operations.[181]

> "We've been playing catch-up for some time," he says. "The problem in the nuclear business is that you are appraised not only on what you do but on what you can demonstrate that you've done. The

> trick is that you have to get the right balance between documenting that you are doing all the right things without tying up so many people that they're not doing their normal jobs as well as they should."

Clearly, first operators are in short supply and fulfill a demanding role at nuclear generating stations. Additional safety audits recommended by the Hare Commission and others would require particular attention by senior operational staff, so that, without additional manpower being provided, the present, reportedly stressful, conditions are unlikely to diminish.

A general conclusion of the Ontario Nuclear Safety Review was that actual performance of individuals and institutions is the key to future safety. There must be a sound safety culture and it must be directed from the top down.[182]

The major conclusion of the Hare Commission related to the overall safety of CANDU nuclear stations in Ontario:[183]

> The Ontario Hydro reactors are being operated safely and at high standards of technical performance. No significant adverse impact has been detected in either the work-force or the public.
>
> The risk of accidents serious enough to affect the public adversely can never be zero, but is very remote.

Ontario Hydro completed preparation of its initial response to the findings and recommendations of the Hare Commission in August of 1988, but the Ontario Ministry of Energy had not authorized Hydro to release its response or comment on its conclusions at the time this paper was being prepared.[184] The Ministry of Energy reportedly intended to coordinate reactions to the Hare report from Ontario Hydro, provincial ministries and the Atomic Energy Control Board, but to date these findings have not been made public. Hydro indicates that is has taken and continues to take action on issues raised by the Hare Commission, and that it has appointed an advisory committee on nuclear safety to keep the organization up-to-date on safety-related matters. This committee, recently appointed by the President of Ontario Hydro, includes Dr. Ken Hare and other former colleagues from the Ontario Nuclear Safety Review among its membership.

The success of Ontario Hydro and other operators of CANDU systems in maintaining and enhancing the high standard of human performance will be a key factor in ensuring the risk of severe nuclear accidents remains "remote." As one reviewer concluded, "the prevention of catastrophic accidents at nuclear power plants depends essentially on the careful, correct fabrication, construction, operation, and maintenance of the reactors, and not on any inherent limitations of reactor eruptions or inherent containment capacities of the reactor containment structures to absorb eruptions and contain the radioactivity, should a mishap occur."[185]

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APPENDIX

Glossary of Technical Terms, Acronyms and Scientific Units

Source: Ontario Nuclear Safety Review.

GLOSSARY

1. Technical Terms

Accident Analysis: quantitative analysis performed to simulate the consequences of postulated nuclear reactor accidents.

Adjustor Rod: a rod of neutron-absorbing material inserted into or removed from the reactor to "adjust" reactor power or reactivity.

Background Radiation: the natural ionizing radiation of the environment, including cosmic rays from outer space, naturally radioactive elements in the ground, and naturally radioactive elements in a person's body.

Baseload: the supply of electricity needed to meet the minimum demand for electricity during a period of time.

Becquerel: a unit of radioactivity equal to one disintegration per second. It is a measure of the rate at which a radioactive material decays. Abbreviated Bq. See also curie.

Boiling Water Reactor (BWR): a nuclear power reactor cooled and moderated by light water. The water is allowed to boil in the core to generate steam, which passes directly to the turbine.

Calandria (vessel): a cylindrical reactor vessel, which contains the heavy water moderator. It is penetrated from end to end by hundreds of calandria tubes which provide sites for the pressure tubes.

Calandria Tube: a tube, welded to the calandria vessel, surrounding the pressure tube in each fuel channel.

CANDU: a Canadian-developed nuclear power reactor system, which uses a pressure tube reactor, heavy-water moderator, and natural uranium fuel. The moderator is separate from the reactor coolant and is maintained cool and at low pressure. The pressure tubes, centrally located within each calandria tube, contain the fuel and the high pressure coolant as it passes through the reactor.

Chain Reaction: a reaction that initiates its own repetition. In a nuclear fission a neutron induces a fissile nucleus to fission, thus releasing several neutrons. To sustain the reaction, at least one of these neutrons must induce another fission.

Collective Dose: the sum of the doses received by a group of exposed individuals.

Commissioning: those activities performed subsequent to installation but prior to plant operation that are intended to show that equipment and systems meet their design requirements.

Common-mode Event: an event that can simultaneously affect several plant systems at one or more reactors at a time. A loss of electrical power and an earthquake are examples of such events.

Containment: the reinforced concrete structure(s) that houses the reactor and its closely-related systems. It is designed to suppress and contain the results of a fracture of the reactor coolant piping.

Core: the central region of a reactor where the nuclear chain reaction takes place, and heat is thereby generated.

Critical: an assembly of nuclear materials is critical if it is just capable of supporting a nuclear chain reaction.

Curie: a measure of the rate at which a radioactive material disintegrates. A curie is the radioactivity of one gram of radium and is named after Pierre and Marie Curie, the discoverers of the radioactive elements radium, radon and polonium. One curie corresponds to 3.7×10^{10} disintegrations per second. Historical unit, replaced by the "becquerel."

Decommission: a process of permanently closing down a nuclear generating station, including the disassembly of the station components and the removal of spent fuel.

Delayed Hydride Cracking: the fracture of hydride concentrations, especially on the outside surface of pressure tubes.

Design-basis Accident: a type of reactor accident considered in setting design requirements for plant equipment and systems.

Dose: a measure of biological damage caused by exposure to ionizing radiation (measured in sieverts or rems). Note: formally, the term "dose" is now used to describe the amount of ionizing radiation energy absorbed per unit mass (measured in grays or reds). What the Hare Commission referred to as dose is now called "dose equivalent."

Dual Failure: the malfunction of a process system occurs simultaneously with the malfunction of a safety system.

Effective Dose Equivalent: the summation of doses to individual organs using weighting factors recommended by ICRP.

Effective Dose Equivalent: the prescribed limit for effective dose (equivalent).

Emergency Coolant Injection System: a special safety system designed to inject cool water into the heat transport system following a pipe rupture.

Enriched Fuel: nuclear fuel containing more than the natural abundance of fissile atoms.

Exclusion Boundary: an area (nominally of 1-km radius) around a nuclear generating station under control of the reactor owner.

Failure: a change in the characteristics of a component or system such that it is unable to carry out its function.

Fast Breeder Reactor (FBR): a reactor in which fast neutrons sustain the fission chain reaction. The fuel is enriched, and a blanket of fertile material surrounding the core captures neutrons to become fissile.

Fissile Material: nuclear fuels in which the nuclei, when hit by neutrons, fission and release energy plus two or more neutrons, which can result in a chain reaction. Uranium-233, uranium-235 and plutonium-239 are examples of significant fissile materials, but only uranium-235 occurs naturally in relatively large quantities.

Fission: the splitting of a heavy nucleus into two parts accompanied by the release of energy and two or more neutrons. It may occur spontaneously or be induced by capture of bombarding particles, particularly neutrons.

Fuel Bundle: an assembly of fuel elements (fuel sheaths containing nuclear fuel pellets) and end plates, ready for insertion into a reactor.

Fuel Channel: the set of components, consisting of the pressure tube, calandria tube, and end fittings, in which the reactor fuel is located.

Fuel Element: small unit of fuel contained within the fuel bundle.

Fuelling Machine: equipment used to load and unload fuel bundles. CANDU fuelling machines are remotely controlled and load the fuel while the reactor is operating.

Fuel Sheath: tubing into which fuel pellets are inserted and sealed to create a fuel element.

Gas-Cooled Reactor: a nuclear reactor in which a gas, such as carbon dioxide, is used as the coolant.

Gray: the SI unit for dose of ionizing radiation. One gray is absorbed when one joule of energy is imparted to each kilogram of matter by ionizing radiation. One gray equals 100 reds. Abbreviated Gy.

Half-Life: the time in which the number of nuclei of a particular type is reduced by radioactive decay to one-half.

Heat Exchanger: a piece of apparatus that transfers heat from one medium to another. A typical example is the steam generator in the CANDU system, where the hot pressurized water coolant is used to convert ordinary water into steam to drive the turbine.

Heavy Water: water in which the hydrogen atoms consist of deuterium, the heavy stable isotope that is present to the extent of 150 parts per million in ordinary hydrogen; used as moderator and coolant in CANDU nuclear reactors.

High-Level Wastes: the irradiated fuel is the most important high-level waste. Also included are other items such as recovered fission products and certain ion exchange resins.

Hydride Blister: a high concentration of deuterium, especially on the outside of a pressure tube.

Irradiated Fuel: fuel that has been exposed to irradiation in a nuclear reactor. If irradiated to its maximum economic life, it is also termed "spent fuel."

Isotopes: nuclei of the same chemical element that differ in mass.

Kilowatt-Hour: a quantity unit of energy, e.g., electrical power delivered at a sustained rate of one kilowatt for a period of one hour.

Light Water: ordinary water.

Loop: a closed circuit of heat transport system piping.

Loss of Regulation Accident: a reactor accident in which the power control (regulating) system malfunctions, resulting in a change in reactor power.

Loss of Coolant Accident: a nuclear reactor accident in which the coolant drains out from the heat transport system.

Low-Level Waste: this is a general term to describe the reactor wastes that arise in the day-to-day operation of the station. It includes such items as water purification filters, certain ion-exchange resins, wiping cloths, protective clothing, etc. Regardless of its general category, each type of waste product is dealt with according to the problem it presents.

Megawatt (MW): one million watts (or one thousand kilowatts). A unit used to indicate the power rating of very large energy-producing (or using) equipment, e.g., generating stations, nuclear reactors, boilers, engines, etc.

Melt-Down: a nuclear reactor accident in which some or all of the reactor fuel melts and cannot be contained within the heat transport system.

Moderator: a substance used to slow down neutrons emitted during nuclear fission (heavy water in the case of the CANDU system).

Natural Uranium: uranium whose isotopic composition as it occurs in nature has not been altered (0.7% by weight of uranium-235).

Negative Reactivity: see reactivity.

Nuclear Energy: the energy liberated by a nuclear reaction such as fission.

Nucleus: the positively charged core of an atom. All nuclei are made up of protons and neutrons, except for ordinary hydrogen, which has no neutrons. The nucleus contains almost the whole of the mass of the atom, but occupies only a minute part of its volume.

Planning Zone: a zone surrounding a nuclear generating station for which a response to a nuclear reactor accident has been planned.

Plutonium (Pu): a heavy radioactive metallic element with an atomic number of 94 whose principal isotope plutonium-239 is a major fissile material. It is produced artificially in reactors through neutron absorption by uranium-238.

Positive Void Reactivity Coefficient: an effect where an increase of reactor void caused by coolant boiling leads to an increase in reactor reactivity (or power).

Power Excursion: an unplanned reactor power increase.

Pressure Tube: the components of the heat transport system in the reactor core inside of which the fuel bundles reside. Pressurized heavy-water coolant flows through the pressure tube to remove the heat generated by the fuel. See also pressure tube reactor.

Pressure Tube Reactor: a nuclear reactor in which the fuel is located inside a large number of high-strength tubes that penetrate the calandria (which also contains the moderator at low pressure). Pressurized coolant passes through the tubes to remove the heat from the fuel. See also CANDU.

Pressurized Water Reactor (PWR): a power reactor cooled and moderated by light water in a pressure vessel surrounding the core. The water is pressurized to prevent boiling and is circulated in a closed primary loop through a heat exchanger that generates steam in a secondary loop connected to the turbine.

Primary Zone: the zone surrounding a nuclear generating station for which there exists an evacuation plan.

Probabilistic Risk Assessment: a method of calculating both the frequency and consequences of reactor accidents.

Rad: the unit dose of ionizing radiation. One rad is absorbed when 100 ergs of energy are imparted to each gram of matter by ionizing radiation (see rem). Historical unit, replaced by "gray."

Radiation: the emission and propagation of energy through space or matter in the form of electromagnetic waves and fast-moving particles.

Radioactivity: the spontaneous decay of an unstable atomic nucleus into one or more different elements or isotopes. It involves the emission of particles or spontaneous fission until a stable state is reached. Note that radioactivity produces the radiation - the two terms are not equivalent.

Radionuclide: a general term used to describe radioactive nuclei.

Reactivity: a measure of the departure of a reactor from criticality. A positive value means that the release of neutrons is increasing and that the power will rise, and a negative value means that the release of neutrons is decreasing, the power is falling, and the chain reaction could die out.

Reactor Core: mechanically, the structural elements in the reactor that locate and contain the nuclear fuel. In the nuclear physics sense, it includes additionally the fuel and the moderator associated with each fuel cell (fuel channel). See also reactor.

Regulating System: reactor power control system.

Rem: the abbreviation for Roentgen Equivalent Man, the unit of an absorbed dose of ionizing radiation in biological matter. It is the absorbed dose in rads multiplied by a factor that takes into account the biological effectiveness of the radiation. Historical unit, replaced by "sievert".

Retubing: replacement of the pressure tubes of a nuclear reactor.

Risk: an activity with the potential for causing harm. In probabilistic risk assessment, risk is defined as the product of the frequency of a harmful event and the harm caused. Acceptable risk refers to an activity that has been willingly accepted by those bearing the risk once the benefits of that activity and the alternatives to that activity are considered. Tolerable risk refers to activity undertaken with the acquiescence of the risk bearers, but not necessarily with their conscious acceptance.

Roentgen: the unit of exposure to gamma or X-rays. Named after Wilhelm Konrad Roentgen, the discoverer of X-rays in Munich in 1895.

Safety Culture: a set of attitudes among designers, managers, and operating staff at a nuclear generating station that encourages practices that foster the safe operation of the station.

Safety Design Matrix: a method of probabilistic risk assessment employed by AECL for a limited range of postulated nuclear reactor accidents.

Safety Support Systems: essential process systems that are required for the proper operation of safety systems. Electrical power is an example.

Secondary Zone: the emergency planning zone outside the primary zone where measures such as sheltering, restriction of foods, and similar measures short of evacuation are planned should a nuclear reactor accident occur.

Serious Process Failure: any failure of equipment or procedure that, in the absence of special safety system(s) action, could lead to significant release of radioactive material from the nuclear generating station.

Severe Accident: 1. An accident leading to a large release of radioactive material from a nuclear generating station. 2. An accident that leads to a destruction of the core structure integrity.

Shielding: a mass of material that reduces radiation intensity to protect personnel, equipment, or nuclear experiments from radiation injury, damage or interference.

Shut-Down: termination of the chain reaction in the reactor.

Shut-Down Systems: the special safety systems capable of terminating the chain reaction in the reactor rapidly.

Shut-Off Rod: a neutron-absorbing rod normally kept out of the reactor core that can be rapidly inserted into the core. The entire set of these rods comprises shut-down system 1.

Sievert: the SI unit of absorbed dose equivalent of ionizing radiation in biological matter. It is the absorbed dose in grays multiplied by a modifying factor that takes into account the biological effectiveness of the radiation. Abbreviated Sv.

Significant Event Report: report documenting an unusual event at one of Ontario Hydro's nuclear generating stations.

Special Safety Systems: systems designed to limit or mitigate the consequences of plant process failures and thereby limit the releases of radioactivity to the environment and the public within acceptable limits. These systems are the shut-down systems, emergency coolant injection system, and containment system.

Spent Fuel: nuclear fuel that has been irradiated in a reactor to the extent that it is no longer economical as a power producer, i.e., during irradiation fissionable isotopes are consumed and fission product poisons are accumulated. Term is used interchangeably with "irradiated fuel,"

Statutory Dose Limit: the maximum dose allowed by AECB regulations.

Steam Generator: a vessel consisting of a large number of tubes. The heavy-water coolant flows through the tubes transferring heat through walls of the tubes to boil the feedwater and produce steam to drive the turbine generator.

Tritium: a radioactive isotope of hydrogen with a mass number of three. It has one proton and two neutrons in its nucleus. It is formed in nuclear reactors; also in nature by cosmic radiation.

Turbine Generator: the machine that converts the mechanical energy of the steam created in the steam generator to generate electrical power.

Uranium (U): a heavy, slightly radioactive metallic element with an atomic number of 92. As found in nature it is a mixture of the isotopes uranium-235 (0.7%) and uranium-238 (99.3%). The artificially produced uranium-233 and the naturally occurring uranium-235 are fissile. Uranium-238 is fertile.

Void: vapour or gas, particularly when mixed with liquid in a pipe or enclosed space.

Void (reactivity) Coefficient: coefficient representing the relationship between the fraction of void present in the reactor reactivity.

Zirconium: a naturally occurring metallic element with an atomic number of 40. The material is used extensively in the construction of in-core reactor components because it has a very high corrosion resistance to high-temperature water and low neutron absorption.

2. Acronyms and Abbreviations

AECB	Atomic Energy Control Board (Canada)
AECL	Atomic Energy of Canada Limited
ALARA	as low as reasonably achievable
BEIR	(Advisory Committee on the) Biological Effects of Ionizing Radiation
BWR	boiling water reactor
CANDU	Canada Deuterium Uranium (reactor)
Ci	curie
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection (international society of radiologists, members from 59 countries, budget of $150,000.00. p/a, funding from governments and other national sources, about 2 full-time staff)

LOCA	loss of coolant accident
LWR	light-water reactor
MAGNOX	magnesium oxide reactor
NGD	Nuclear Generation Division (Ontario Hydro)
NGS	nuclear generating station
NRU	National Research Universal reactor (Chalk River Nuclear Laboratories, AECL)
NRX	National Research Experimental reactor
PWR	pressurized water reactor
QA	quality assurance
QC	quality control
TMI	Three Mile Island Nuclear Generating Station of the General Public Utilities System, USA

TABLE OF RADIOLOGICAL QUANTITIES AND UNITS

Quantity	Unit	Symbol	Conversion factor to old units
activity (1)	becquerel	Bq	1 Bq = 2.7×10^{-11} curie
absorbed dose (2)	gray	Gy	1 Gy = 100 rad
dose equivalent (3)	sievert	Sv	1 Sv = 100 rem

Notes:

(1) Activity is the rate of transformation (also known as rate of decay) of a radionuclide. 1 Bq is 1 transformation (or decay) per second.

(2) Absorbed dose is the amount of energy imparted to unit mass of matter (such as tissue) by ionizing radiation. One gray equals one joule per kilogram.

(3) Dose equivalent is the quantity obtained by multiplying the absorbed dose by a factor to allow for the different effectiveness of various ionizing radiations in causing harm to tissue.